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AN EXPERIMENTAL INVESTIGATION IN A MODEL TUNNEL TO DETERMINE THE STARTING AND RUNNING PRESSURE RATIO REQUIREMENTS OF THE PWT 16-FOOT SUPERSONIC TUNNEL AT M = 3.5 TO 6.0

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Propulsion Wind Tunnel Facility
ARO, Inc.

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AN EXPERIMENTAL INVESTIGATION IN A MODEL TUNNEL TO DETERMINE THE STARTING AND RUNNING PRESSURE RATIO REQUIREMENTS OF THE PWT 16-FOOT SUPERSONIC TUNNEL AT M = 3.5 TO 6.0

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Propulsion Wind Tunnel Facility
ARO, Inc.
a subsidiary of Sverdrup and Parcel, Inc.

November 1964

ARO Project Nos. PS2407 and PS3506

ABSTRACT

A determination of the minimum pressure ratios required for starting and running in the PWT, Supersonic (16S) was required in the Mach number range from 3.5 to 6.0 because of the work now in progress to extend the Mach number range of that facility. Estimates of these requirements were determined by tests in the AWT, Supersonic (1S) model tunnel. For these tests the variable geometry diffuser contained a closed-off scoop, and a model was installed in the test section.

The results of these tests indicate that for Tunnel 16S the minimum starting pressure ratio requirements vary from 58 percent normal shock recovery at M_∞ = 3.50 to 45 percent at M_∞ = 5.85. The minimum running requirements vary from 112 percent normal shock recovery at M_∞ = 3.50 to 85 percent at M_∞ = 5.85.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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ILLUSTRATIONS

NOMENCLATURE

A^{**}	Second throat area, ft^2
A_T	Entrance area of diffuser for $\theta_w = 0$, ft^2
$A_{T\theta}$	Entrance area of diffuser for variable θ_w, ft^2
K	Contraction ratio correction factor $A_T/A_{T\theta}$
M_∞	Nominal test section Mach number
p_{t_e}	Diffuser exit pressure, psf
p_{t_o}	Stilling chamber pressure, psf
T_{t_o}	Stilling chamber temperature, °F
δ	Test section-diffuser gap, in.
θ_w	Test section wall angle, min (positive for wall divergence)
λ	Tunnel pressure ratio, p_{t_o}/p_{t_e}
ψ	Diffuser contraction ratio, $A^{**}/A_{T\theta}$
$\exists$	Designates minimum contraction ratio for starting or running

1.0 INTRODUCTION

Work is now in progress on ducting which will permit operation of the main compressor of the Propulsion Wind Tunnel, Supersonic (16S) in series with the Plenum Evacuation System. This series operation will permit the extension of the maximum Mach number of Tunnel 16S from 4.0 to beyond Mach 6.

Tunnel 16S starting and running pressure ratio requirements in the Mach number range from 3.5 to 6.0 are presently unknown and hence, can only be estimated by using data from other supersonic wind tunnels. The Supersonic Tunnel Association has compiled such data which indicate in general that supersonic wind tunnels run and start at pressure ratios associated with normal shock and 50 percent normal shock recovery, respectively. These data are inadequate for accurately estimating 16S pressure ratio requirements.

A test program was conducted in the Aerodynamic Wind Tunnel, Supersonic (1S), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), to determine more accurately the minimum starting and running pressure ratio requirements for Mach numbers in the range from 3.5 to 6.0. Pressure ratio data below Mach number 3.5 were obtained to correlate Tunnel 1S data with Tunnel 16S data.

2.0 APPARATUS

2.1 GENERAL

The Aerodynamic Wind Tunnel, Supersonic (1S) is a continuous-flow, non-return tunnel which utilizes the air supply and exhauster capabilities of the Rocket Test Facility. Tunnel 1S is a 1/16-scale model of the test leg of Tunnel 16S. The tunnel can be operated within a total pressure range of 1400 to 6500 psfa and a Mach number range of 1.5 to 6.0. The general layout of the tunnel and its associated equipment is shown in Fig. 1, and a detailed description of the tunnel components and operating characteristics can be found in Ref. 1.

2.2 TEST SECTION AND DIFFUSER

The test section, which is enclosed by four solid walls, is 12 by 12 in. in cross section and 30 in. long. The two sidewalls are fixed; the top and

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bottom walls are hinged at the exit of the semi-flexible nozzle and attached to screw actuators at the downstream end to allow for variation in wall angle.

The diffuser is composed of a variable-geometry section followed by a fixed section with a transition from rectangular to circular cross section. Extending throughout the diffuser is a circular scavenging scoop. A closed aerodynamic tip was installed upon the scoop for these tests.

The variable-geometry diffuser, which is 75 in. long, has fixed, parallel sidewalls spaced 12 in. apart and has movable upper and lower walls, each of which consists of five straight, hinged sections. Various diffuser configurations may be obtained by manual adjustments of screw-jacks which are attached to the top and bottom walls at each joint. These components are shown in Fig. 2.

2.3 TEST ARTICLES

To simulate typical tests in Tunnel 16S, a model of the 16S strut and sting support system was installed in the test section for the principal portion of the investigation. A cone-cylinder body was mounted on the sting of this support system with the tip extending to station -1.8 (station 0 is at the upstream end of the test section). This assembly, which is shown in Fig. 2, created a test section blockage of 4 percent.

For simulation of the 16S calibration entry, a 1/16-scale model of the 16S traversing calibration probe was installed in the test section with the tip extending to station -5.5. This assembly, which is shown in Fig. 3, created a test section blockage of 8 percent.

Ducting can be used to separately remove air from the diffuser exit, plenum chamber, and scavenging scoop (see Fig. 1). Air removal from the diffuser exit and plenum chamber has become normal operation in 1S and hence, the gap between the test section and diffuser is sealed as is shown in Fig. 4. The 16S plenum, however, is evacuated through a test section diffuser gap, which is nominally set at one inch. To simulate this condition, appropriate fairings were fabricated and mounted on the end of the test section. This installation is shown in Fig. 5.

A boundary-layer rake was installed at station 2.3 as is shown in Fig. 3. Data from this rake are not presented in this report.

2.4 INSTRUMENTATION

Measurements of stilling chamber, test section static, and diffuser exit total pressures were made with differential transducers, referenced to vacuum, and displayed on electromanometers. A 60-psia transducer was used to measure stilling chamber pressure, and 15-psia transducers were used to measure the test section static and diffuser exit total pressures. In addition, all pressures were photographically recorded from a 120-in., 100-tube mercury manometer.

3.0 PROCEDURE

3.1 TEST CONDITIONS

This investigation was conducted over a Mach number range of 2.50 to 6.00, and the stilling chamber pressure was varied from 2100 to 6200 psfa as necessary to provide the pressure ratio required to establish supersonic flow at each Mach number. The stagnation temperature was held nominally at 110°F. This procedure for setting stagnation conditions led to a slight variation in Reynolds number; however, this was neglected in the data analysis.

3.2 DISCUSSION OF VARIABLES

The major variables of interest were as follows:

1. Test section Mach number, M_∞
2. Diffuser configuration
3. Diffuser contraction ratio, ψ
4. Test section wall angle, θ_W
5. Test section-diffuser gap, δ
6. Test section model configuration

Ten test section Mach numbers were run, and these were divided into three ranges with a different emphasis placed upon each range.

Mach numbers of 2.50, 3.00, 3.25, and 3.50 were investigated primarily to define the correlation of Tunnel 1S data with Tunnel 16S data. Particular emphasis was placed upon Mach numbers 4.00, 4.25, and 4.50 since previous matching calculations for the proposed mode of operation indicated that this would be the probable range for starting supersonic flow. Data were also obtained at Mach numbers 5.00, 5.50, and 5.85 with the intention that these data would be utilized to predict the running requirements of Tunnel 16S in this range.

These tests were conducted utilizing either of two variable-geometry diffuser configurations which were identical with the 16S configurations designated as "A" and "B" contours. These contours have been generated with the area of the second throat as the independent variable. Considering the symmetry of the diffuser, the "A" family uses one leaf for the supersonic diffuser, and two leaves each for the near-constant area section and for the subsonic diffuser. The "B" family has two leaves each for the supersonic diffuser portion and for the throat section and one leaf for the subsonic diffuser. Figure 6 shows a comparison of representative "A" and "B" family configurations. For this investigation the variation of the diffuser contraction ratio, ψ, was from 0.485 to 0.990 and from 0.335 to 0.940 for the "A" and "B" contour families, respectively.

Variation of the wall angle at each Mach number was limited by the stresses exerted in the nozzle plates. A design test section wall angle was defined as that angle which is equal to the nozzle exit angle. The minimum, maximum, and design test section wall angles are shown in Fig. 7 as a function of Mach number for $M_\infty \geq 4.0$. The allowable wall angle variation below $M_\infty = 4.0$ was not defined. The overall variation in wall angle, independent of Mach number, was from -30 to +90 min.

The test section-diffuser gap is the step between the test section wall and the diffuser wall, not the longitudinal gap. The zero setting ($\delta = 0$) is with the diffuser aligned with the test section and sealed as shown in Fig. 4. Variations in the gap were made to simulate those in Tunnel 16S by installing the fairings shown in Fig. 5. The gap variation was from 0.063 to 0.50 in. A minimum of 0.063 in. clearance was always maintained between the diffuser flap and the fairing. This 0.063-in. gap simulated the 1-in. gap typically used in Tunnel 16S.

Before the investigation could be conducted, it was necessary to establish nozzle contours for Mach numbers above 4.50. These contours were established by the methods outlined in Ref. 2.

3.3 TEST DESCRIPTION

The test was divided into several phases, and the various combinations of test variables are summarized in the table on the following page for the cone-cylinder, sting support configuration:

"A" Family				"B" Family	
	Starts		Breaks		Start	Break
δ =	0	0.063	0	0.063	0	0
M	← θ_w →				← θ_w →	
2.5	-30	-30	-30	-30	-30	-30
3.0	-30	-30	-30	-30	-30	-30
3.25	-30	-30	-30	-30	-30	-30
3.5	-30		-30		-30	-30
4.0	0	0	0	0	0	0
4.25	8	8	8	8	8	8
4.50	17	17	17	17	17	17
5.0	34		34		34	34
5.5	54		54		54	54
5.85	70		70		70	70

A test section wall angle of -30 min was used for all investigations in the low Mach number range ($2.5 \leq M \leq 3.5$), since it was shown to be optimum in Ref. 3.

Diffuser performance was obtained with the calibration rig installed and a gap setting of 0.063 in. The data were obtained at the design wall angle for Mach numbers 4.00 and 4.25 and at the minimum wall angle for Mach number 4.50.

3.4 METHOD OF OBTAINING DATA

The general testing technique for each run was to adjust the stagnation and exhauster pressures to provide an abundance of pressure ratio for establishment of supersonic flow at each Mach number. Then for various contraction ratios, a downstream control valve was throttled and unthrottled to increase or decrease the diffuser exit pressure and hence, decrease or increase the tunnel pressure ratio. The valve was gradually controlled until flow breakdown or establishment occurred.

Significant and rapid changes in the test section static pressure at flow start or breakdown were evident on the test instrumentation, and this indication was used to establish the instant of flow start or breakdown. At this instant the pertinent data were recorded.

Generally, the minimum contraction ratio for which starting could be obtained was determined by providing sufficient pressure ratio and increasing the diffuser area in small increments until flow started. The diffuser breakdown contraction ratio, the point at which the area of the second throat becomes insufficient to handle the tunnel mass flow and maintain a supersonic test section, was obtained by slowly closing the diffuser until the diffuser would choke and flow breakdown would occur.

3.5 DATA REDUCTION, CORRECTIONS, AND ACCURACY

The tunnel pressure ratio, λ, was defined as the ratio of the stagnation pressure, p_{t_o}, to the diffuser exit pressure, p_{t_e}. The diffuser exit pressure should normally be measured just downstream of the diffuser. However, because an unsteadiness in the flow in this region had an adverse effect on pressure measurements, p_{t_e} was measured at a station sufficiently downstream to eliminate this effect.

When attempting to correlate the Tunnel 16S and 1S data, ducting loss calculations were made to determine the errors induced into the pressure ratio because of the difference in location of measuring stations. These calculations indicated that this effect, as well as the effect of measuring the 16S compressor inlet pressure with a static orifice, could be neglected since the errors were about the same or smaller than the accuracy of the pressure ratio measurement.

The diffuser contraction ratios as originally defined were based on a zero test section wall angle and also neglected a very small effect of inexact scaling of the 16S scavenging scoop tip. For consistency and to exhibit the effect of wall angle variation, the data were corrected by the following equation:

$$\psi = \frac{A^{**}}{A_{T_\theta}} = \frac{A^{**}}{A_T} \cdot \frac{A_T}{A_{T_\theta}} = K \frac{A^{**}}{A_T}$$

The correction factor K is shown in Fig. 8 for both the 1S and the 16S data.

As previously mentioned the data were obtained from two sources. An accuracy of 1/10 in. of mercury for the manometer data and ±1 count for the transducer data led to the following average pressure ratio uncertainties for the respective Mach number ranges:

Mach Number Range	Mercury Manometer, percent	Transducer, percent
2.50 - 3.50	±1.4	
4.00 - 4.50	±2.6	±1.0
5.00 - 6.00	±6.0	±1.9

Because of its better accuracy, the transducer data were used whenever possible. The exception is the data for the low Mach number range where transducer data were not available.

4.0 RESULTS AND DISCUSSION

4.1 COMPARISON OF 16S AND 1S PRESSURE RATIO REQUIREMENTS

Tunnel 1S data obtained in the low Mach number range, i. e., 2.50 to 3.50, are compared with available Tunnel 16S starting and running pressure ratio requirements for various diffuser contraction ratios in Fig. 9. The 1S data are shown for the "A" and "B" diffuser families, $\theta_W = -30$ min and $\delta = 0$. The 16S data are values that were obtained during several different aerodynamic tests conducted in that facility. The 16S data, for $\delta = 1$ in., were obtained over a test section wall angle range from -30 to +30 min; however, little difference could be noted, hence these points were not distinguished. The 16S data were obtained with a strut and model location that was similar to the 1S installation.

The 1S pressure ratio requirements for starting and running with the "A" and "B" diffusers as a function of diffuser contraction ratio are shown in Fig. 10 for the mid-range Mach numbers and in Fig. 11 for the high-range Mach numbers. These data were obtained at the minimum wall angle for each Mach number and $\delta = 0$.

At $M_\infty = 5.50$ and 5.85 the stagnation temperatures necessary to prevent liquefaction in the test section were not obtained. The temperature deficiencies were 30 and 70°F, respectively, based on Ref. 4. The test section Mach number for the Mach 6 nozzle contour was reduced to 5.85 on the basis of measurements from the boundary-layer rake. There was no measurable effect at $M_\infty = 5.50$.

It is evident from these figures that the "B" family is the better running configuration, and the "A" family is the better starting configuration. Figures 9 through 11 also indicate, by the symbol ( ), the minimum contraction ratio for running and starting at each Mach number, and a summary of these data is shown in Fig. 12.

The minimum starting and running pressure ratio requirements are shown in Fig. 13 as a function of Mach number for both the 1S and 16S wind tunnels. It is noted that in the low Mach number range the 16S "A" family starting and running requirements are greater than those for 1S by approximately 19 and 13 percent, respectively.

It appears reasonable to estimate the 16S starting and running requirements for Mach numbers above 3.50 by extrapolation of the 16S curves beyond $M_\infty \doteq 3.50$ with the same shape as that of the 1S data as shown in Fig. 13.

The extrapolation of the 16S data indicates that the minimum starting pressure ratio requirements range from 58 percent normal shock recovery at $M_\infty = 3.50$ to 45 percent at $M_\infty = 5.85$ (Fig. 13a). The minimum running requirements vary from 112 percent normal shock recovery at $M_\infty = 3.50$ to 85 percent at $M_\infty = 5.85$ (Fig. 13b).

4.2 EFFECTS OF TEST SECTION-DIFFUSER GAP VARIATION

The investigation of gap variation was limited to the "A" diffuser family, since it was previously shown that this configuration provided the best starting performance. Figures 14 and 15 show the comparison of pressure ratio requirements as a function of diffuser contraction ratio for $\delta = 0$ and 0.063, for the low- and mid-range Mach numbers, respectively. A gap setting of 0.063 in. in Tunnel 1S was chosen for comparison as it simulates a gap setting of one inch in 16S which is typically used in that facility.

Figure 16 shows the minimum starting and running pressure ratio requirements for the above data. It is obvious from this figure that the effect of a finite gap on running is greater than that on starting. The requirements of $\delta = 0.063$ are greater than $\delta = 0$ by approximately 8.5 and 16 percent for starting and running, respectively. It should be noted that the effect of increasing the gap from 0 to 0.063 in. accounts for more than the difference between the 16S and 1S running requirements (see section 4.1) and for approximately 38 percent of the difference in starting requirements. These results indicate that a gain in 16S diffuser performance can be obtained by eliminating the 1-in. gap now in use.

Increasing the gap beyond 0.063 in., at Mach numbers 3.25 and 4.25, generally caused the minimum pressure ratio for starting and running to increase.

4.3 EFFECTS OF TEST SECTION WALL ANGLE VARIATION

The effect of θ_W variation was investigated for only the "A" diffuser family and the mid-range Mach numbers. The effect upon starting for a 75-min θ_W variation at $\delta = 0$ was inconclusive; therefore, the data were not presented. The effect of θ_W on running, at $\delta = 0$, is to increase the minimum required pressure ratio as the walls are diverged. The effect of a 43-min variation in θ_W on starting at δ = 0.063 was negligible and therefore was not presented.

4.4 EFFECTS OF TEST SECTION INSTALLATION

All the data previously presented were obtained with the cone-cylinder model installed in the test section. Figure 17 shows a comparison of the cone-cylinder model and the calibration rig installation. The data were obtained for the "A" diffuser family, δ = 0.063, and for the middle Mach number range. Flow was definitely easier to start with the calibration rig installed; however, the comparative running requirements are somewhat inconclusive.

5.0 CONCLUSIONS

Based on the results of this investigation to determine the starting and running pressure ratio requirements of Tunnel 16S, the following conclusions are made.

1. The extrapolation of the Tunnel 16S data indicates that the minimum starting pressure ratio requirements vary from 58 percent normal shock recovery at M_∞ = 3.50 to 45 percent at M_∞ = 5.85. The minimum running requirements vary from 112 percent normal shock recovery at M_∞ = 3.50 to 85 percent at M_∞ = 5.85.

2. The performance of the "A" and "B" diffuser families was clearly defined. The "A" family requires less pressure ratio for starting and more pressure ratio for running than the "B" family.

3. Tunnel 16S, with δ = 1.0, required 19 percent more pressure ratio for starting and 13 percent more pressure ratio for running than did Tunnel 1S with δ = 0.

4. The effect of increasing the test section diffuser gap from δ = 0 to 0.063 in Tunnel 1S was to increase the "A" diffuser family requirements for starting and running 8.5 and 16 percent, respectively. Gap variations beyond δ = 0.063 increased the starting and running requirements. These results indicate that a gain in 16S diffuser performance could be obtained by eliminating the gap in that facility.

5. Test section wall angle variation has a negligible effect on starting, but increasing wall divergence increases running requirements.

6. The calibration rig installation reduced the starting requirements compared to those of a sting-supported, cone-cylinder model. Only a slight difference was found in the minimum running requirements for the two configurations.

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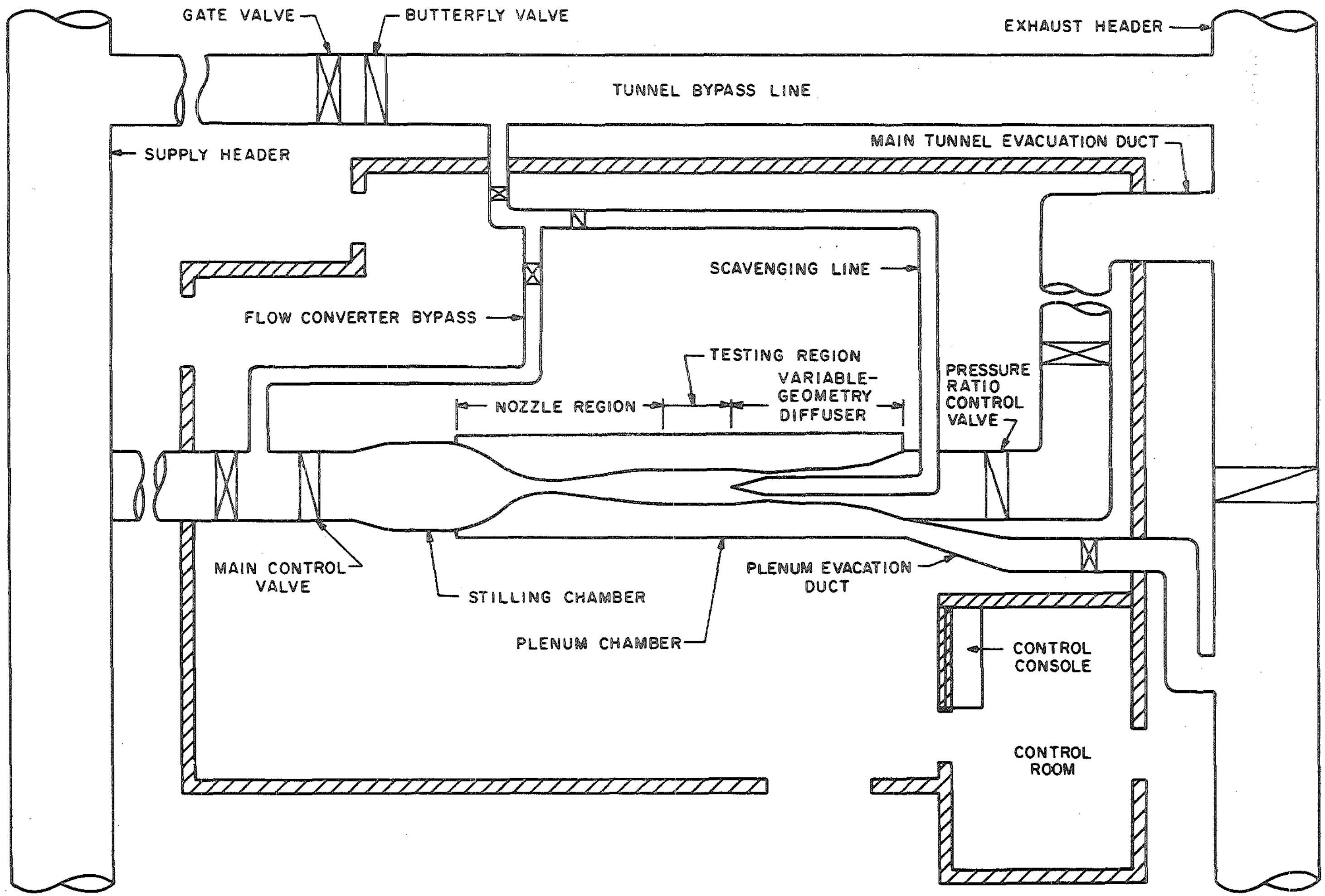

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Fig. 1 General Arrangement of Tunnel 1S and Supporting Equipment

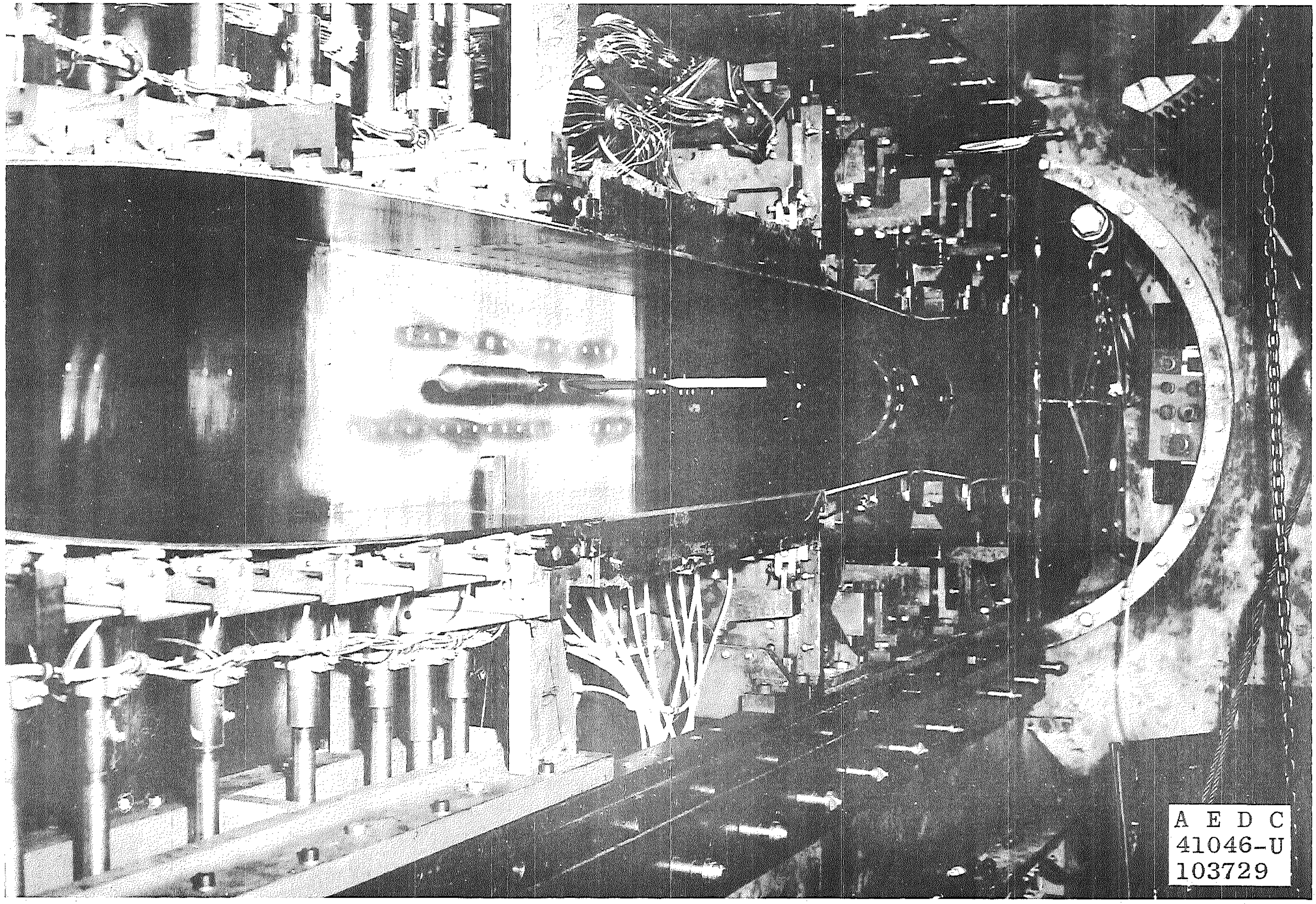


Fig. 2 General View of Tunnel 1S Semi-Flexible Nozzle, Test Section, and Variable-Geometry Diffuser

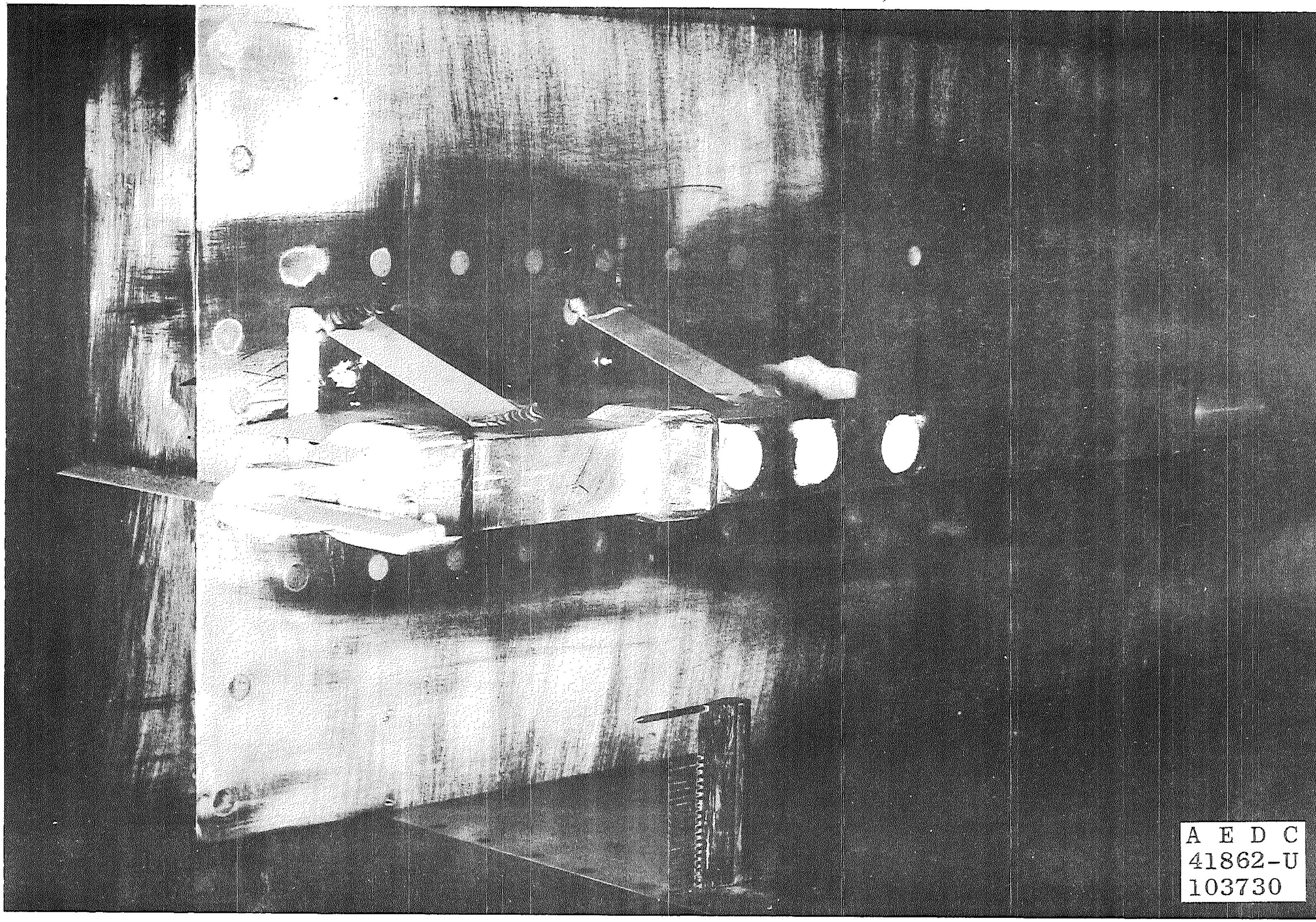


Fig. 3 Installation of the 1/16-Scale Model of Tunnel 16S Calibration Rig

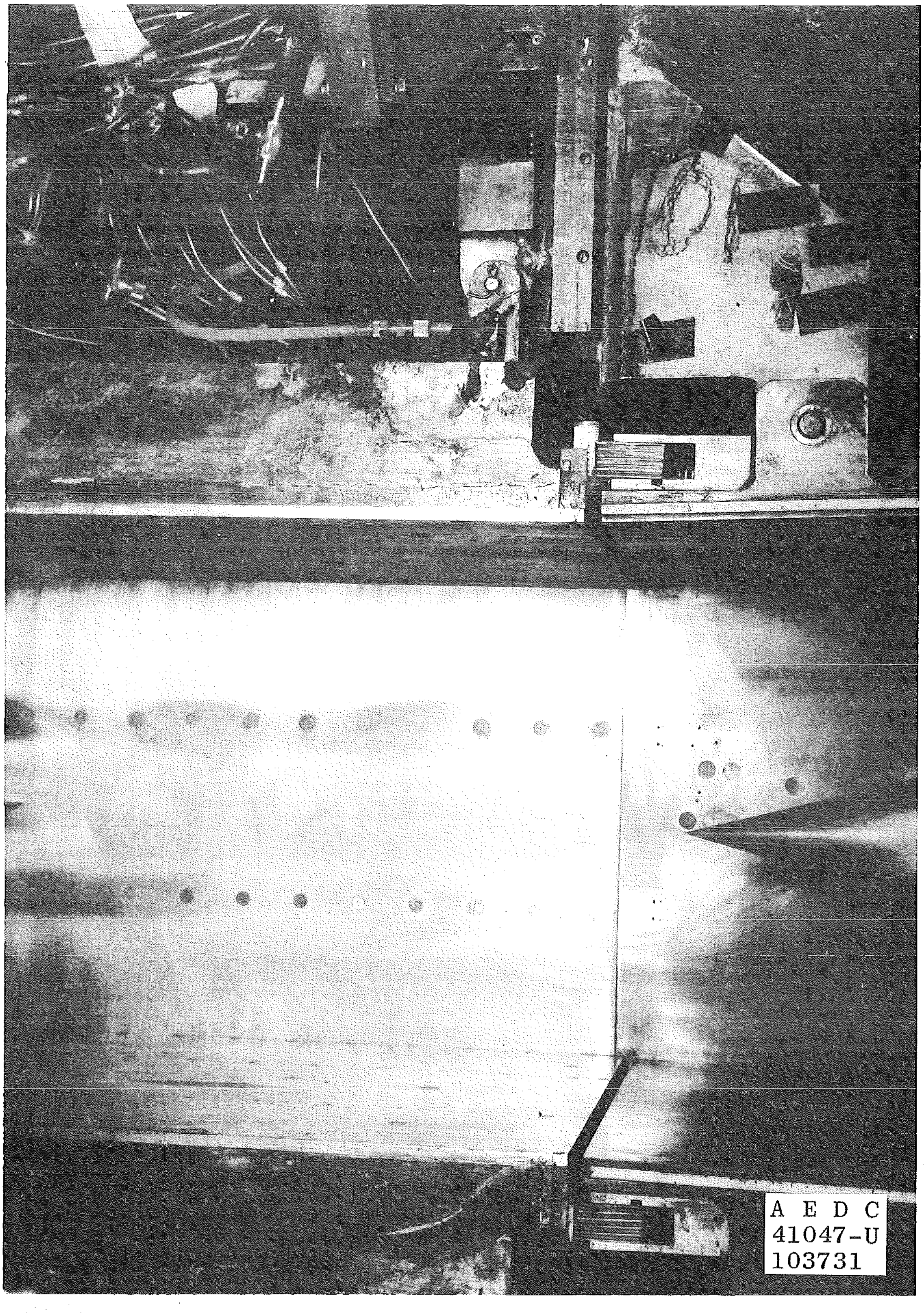


Fig. 4 Test Section-Diffuser Gap Seals

Fig. 5 Fairing Simulating Tunnel 16S Test Section-Diffuser Gap

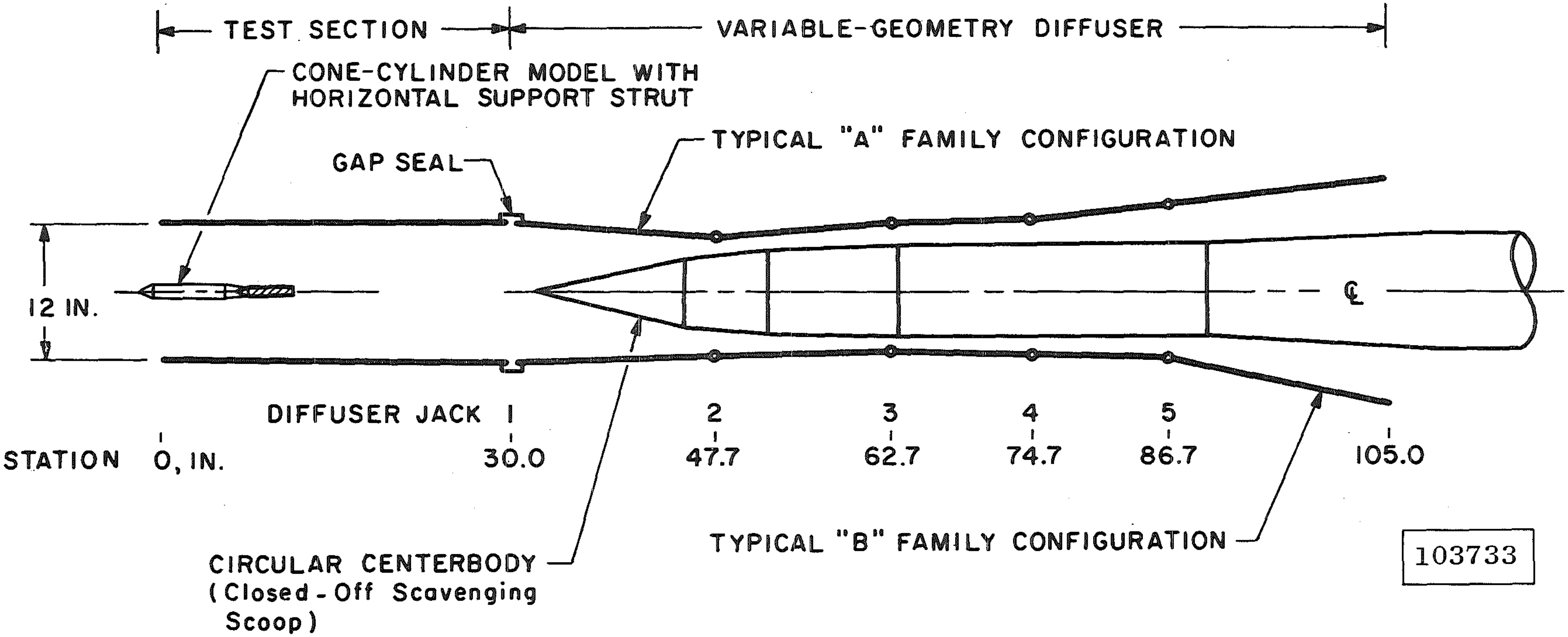


Fig. 6 Schematic of Tunnel 1S Test Leg and Variable-Geometry Diffuser Families

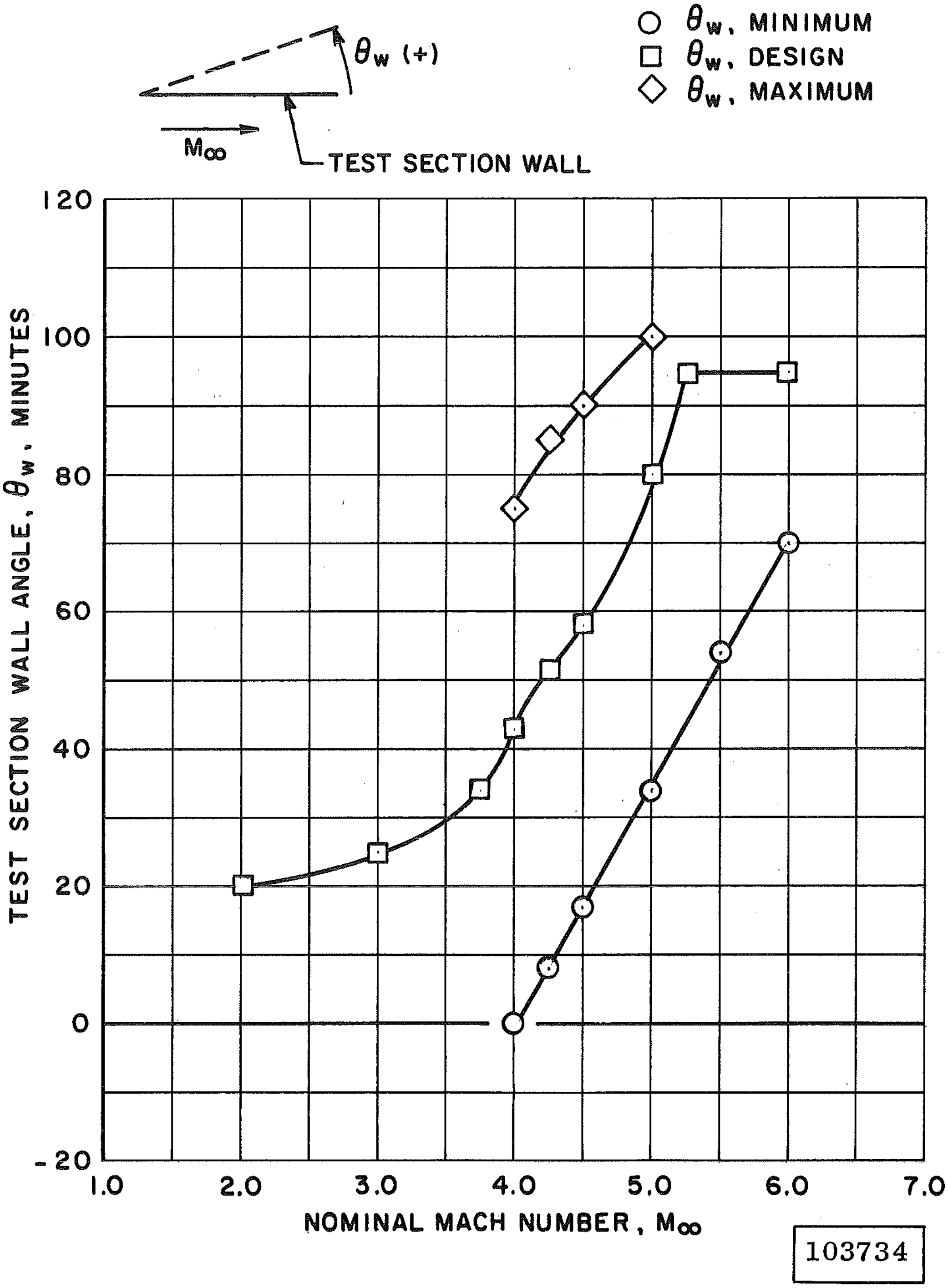


Fig. 7 Effect of Nozzle Structural Limitations on the Test Section Wall Angle for Tunnel 1S

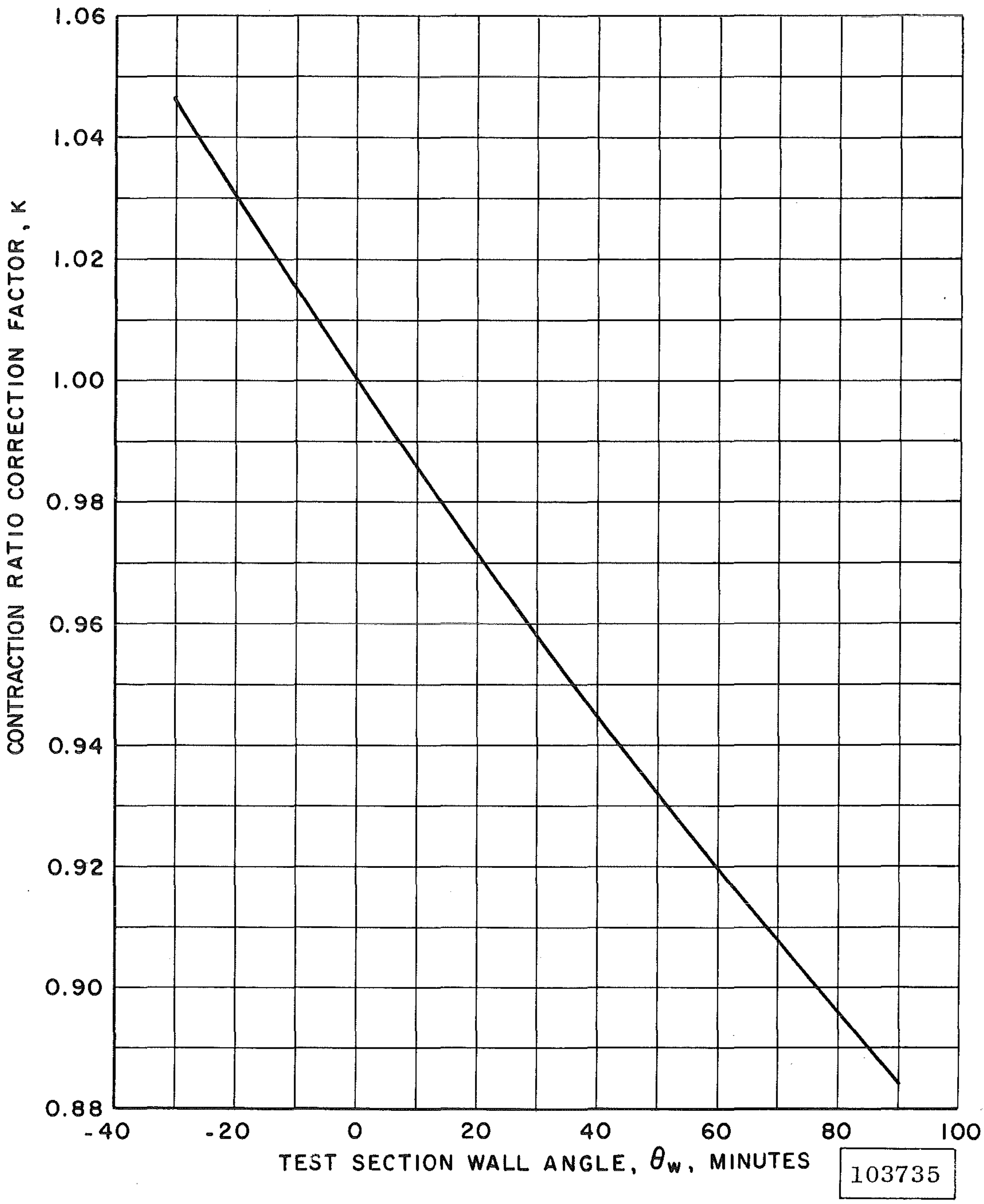
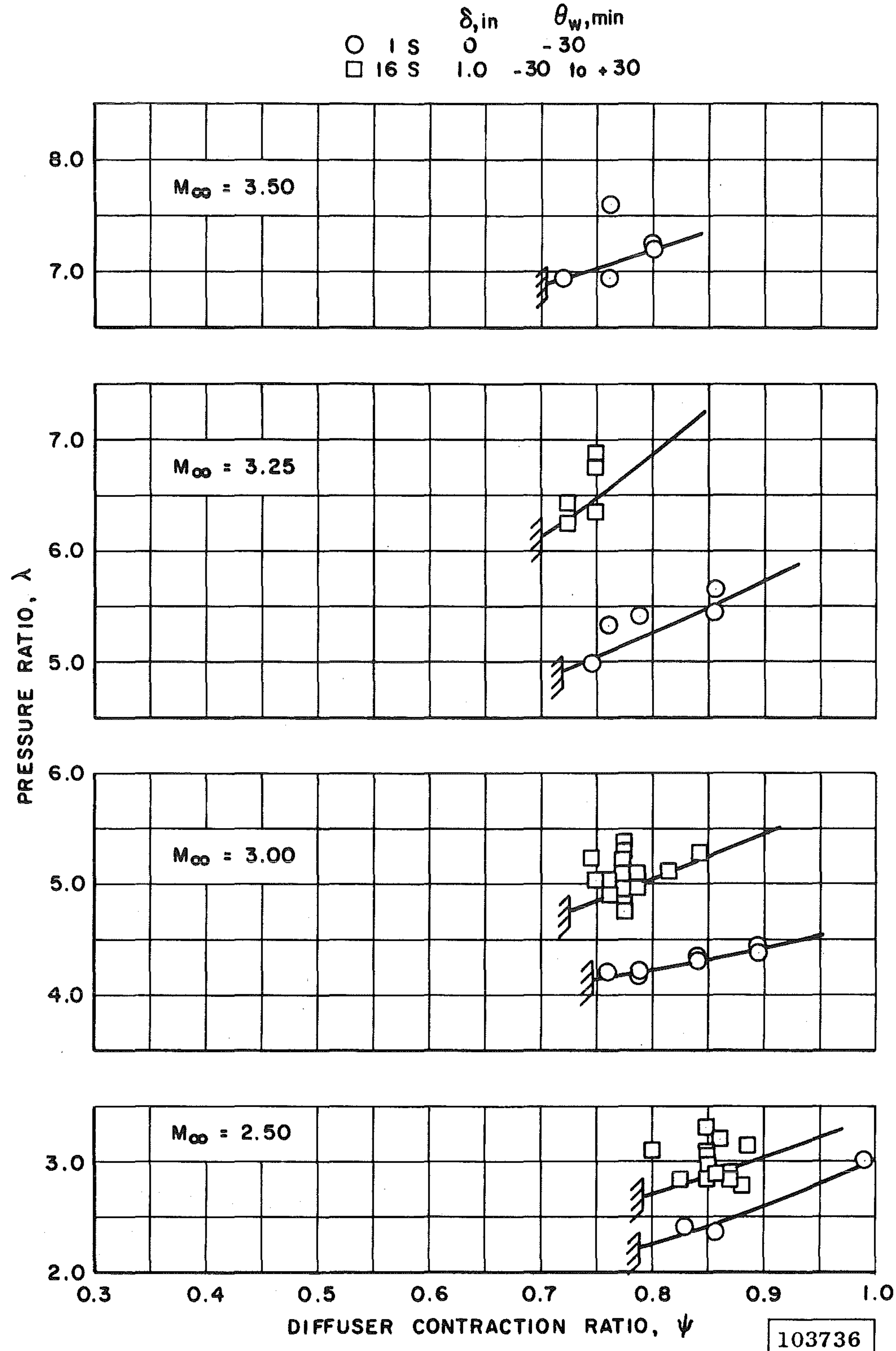
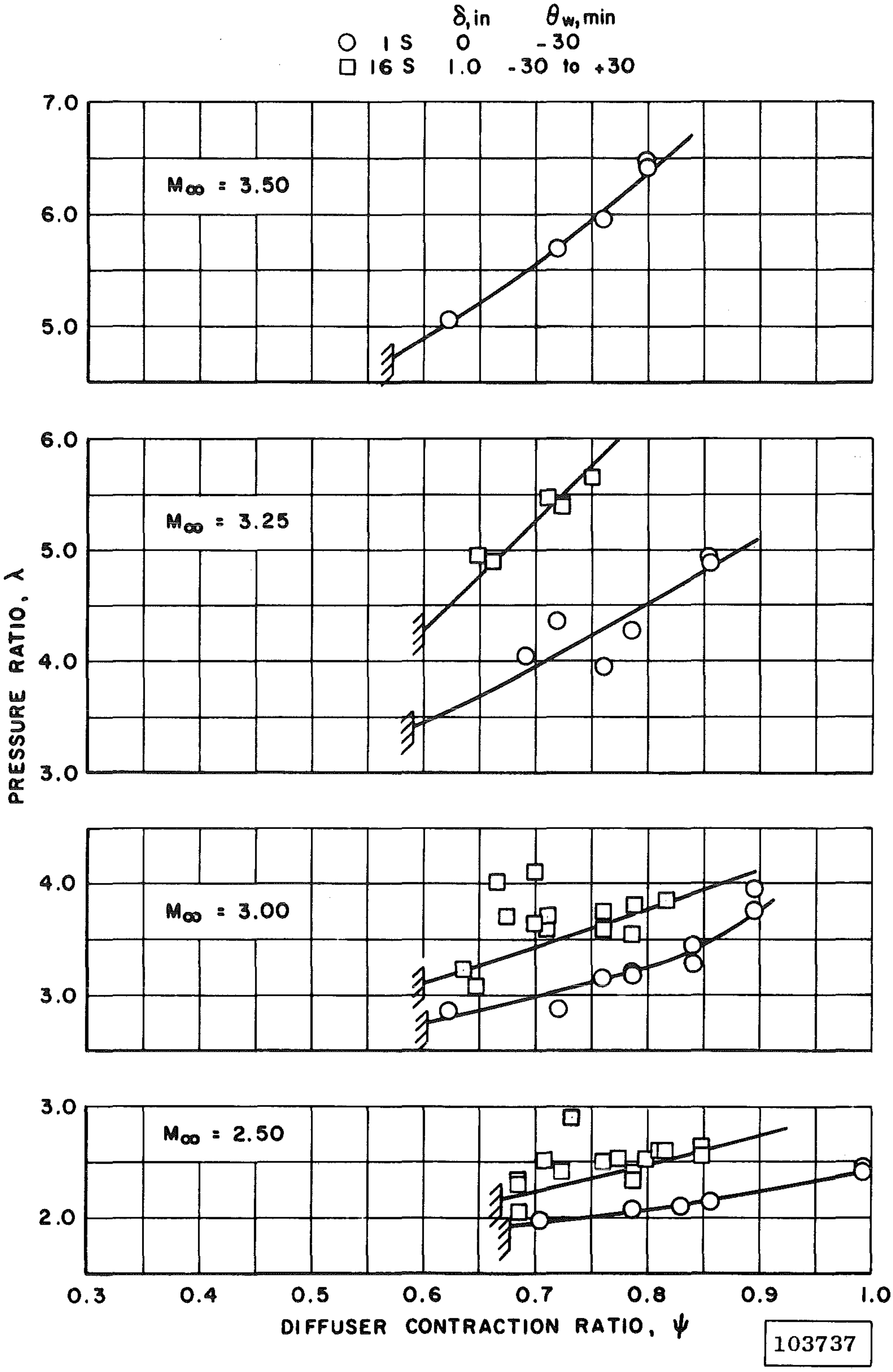


Fig. 8 Contraction Ratio Correction Factor for Tunnels 16S and 1S



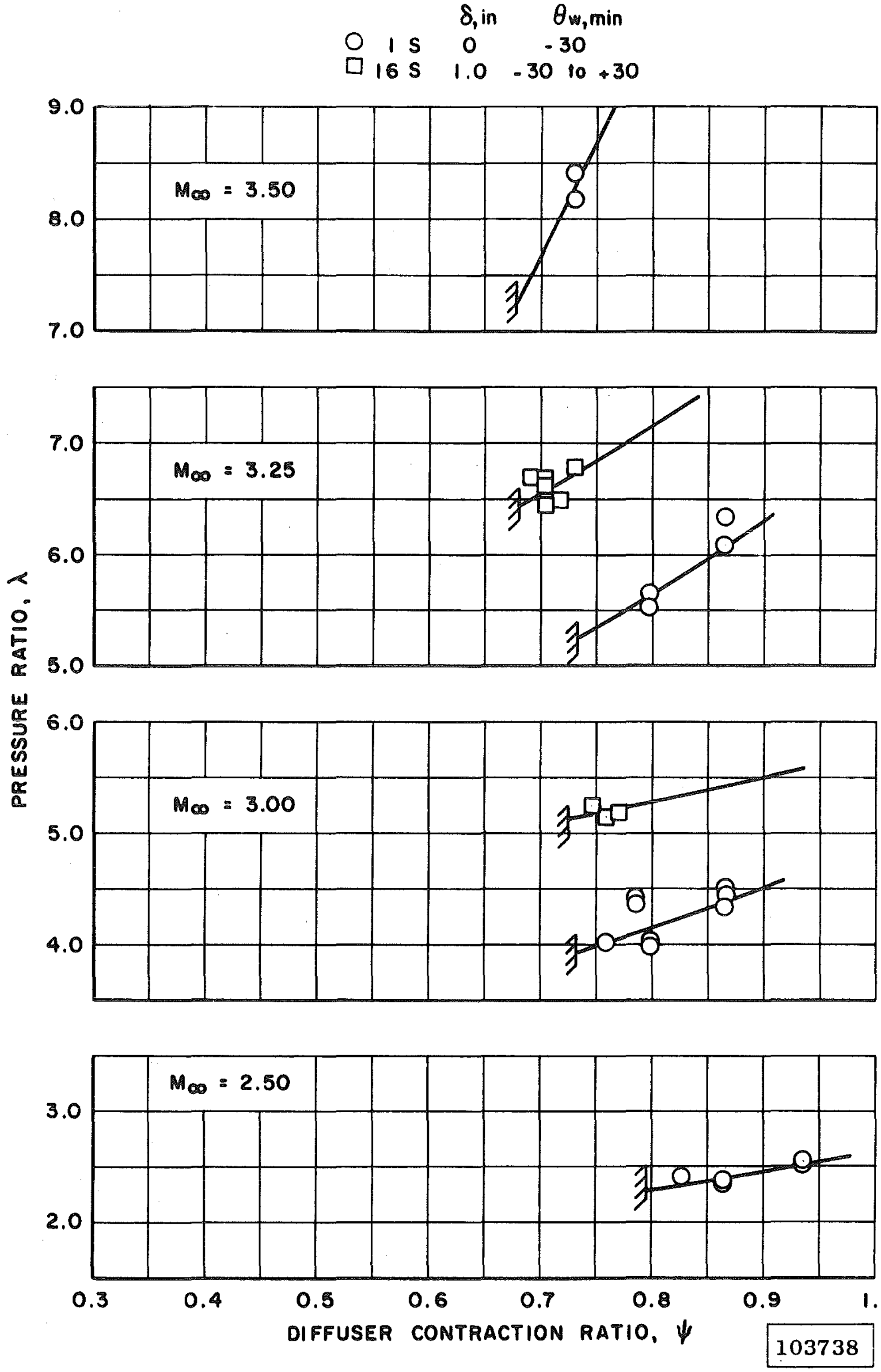
a. "A" Family Starts

Fig. 9 Tunnels 16S and 1S "A" and "B" Families Starting and Running Performance at M_∞ = 2.50, 3.00, 3.25, and 3.50



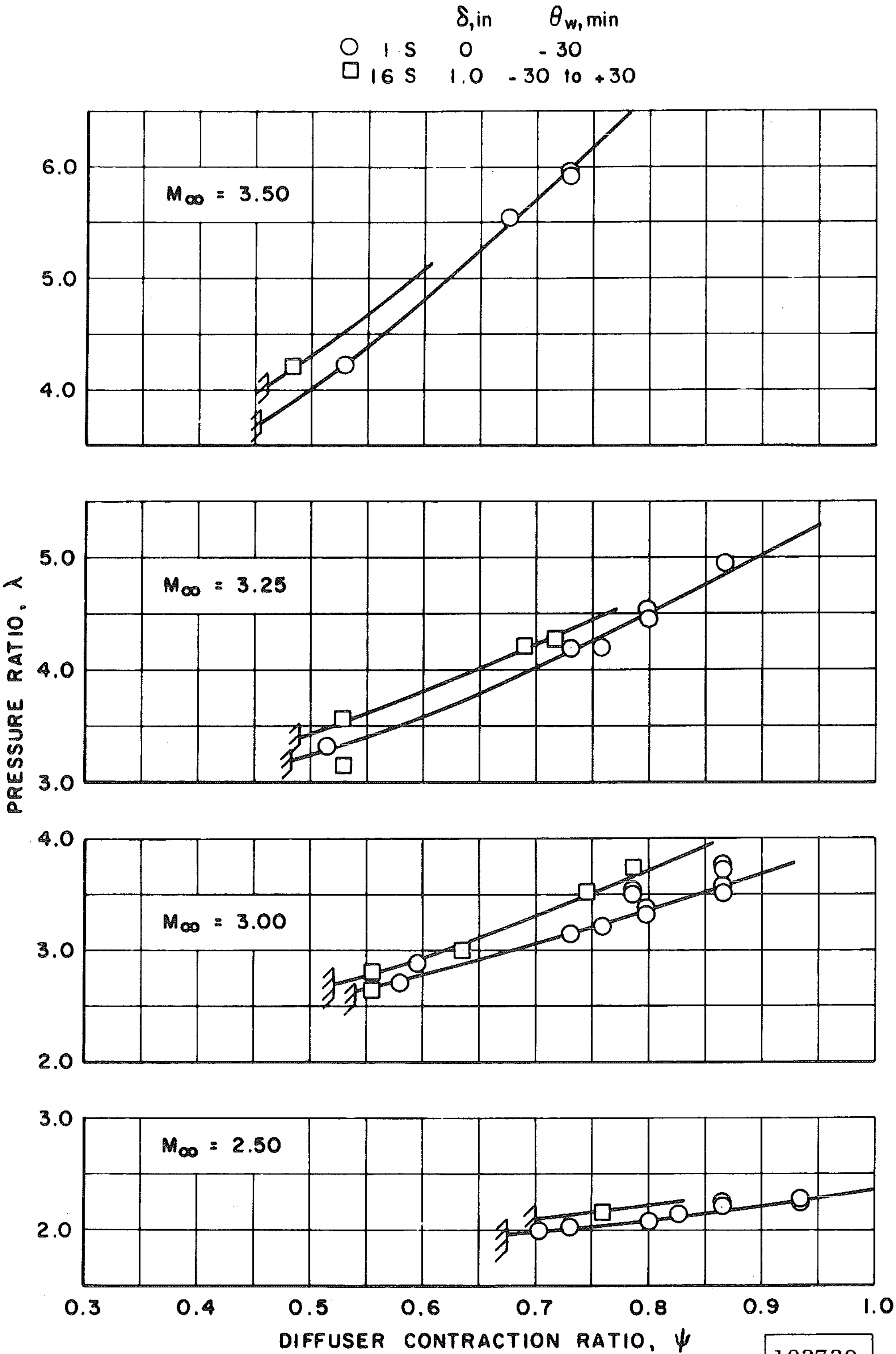
b. "A" Family Breakdowns

Fig. 9 Continued



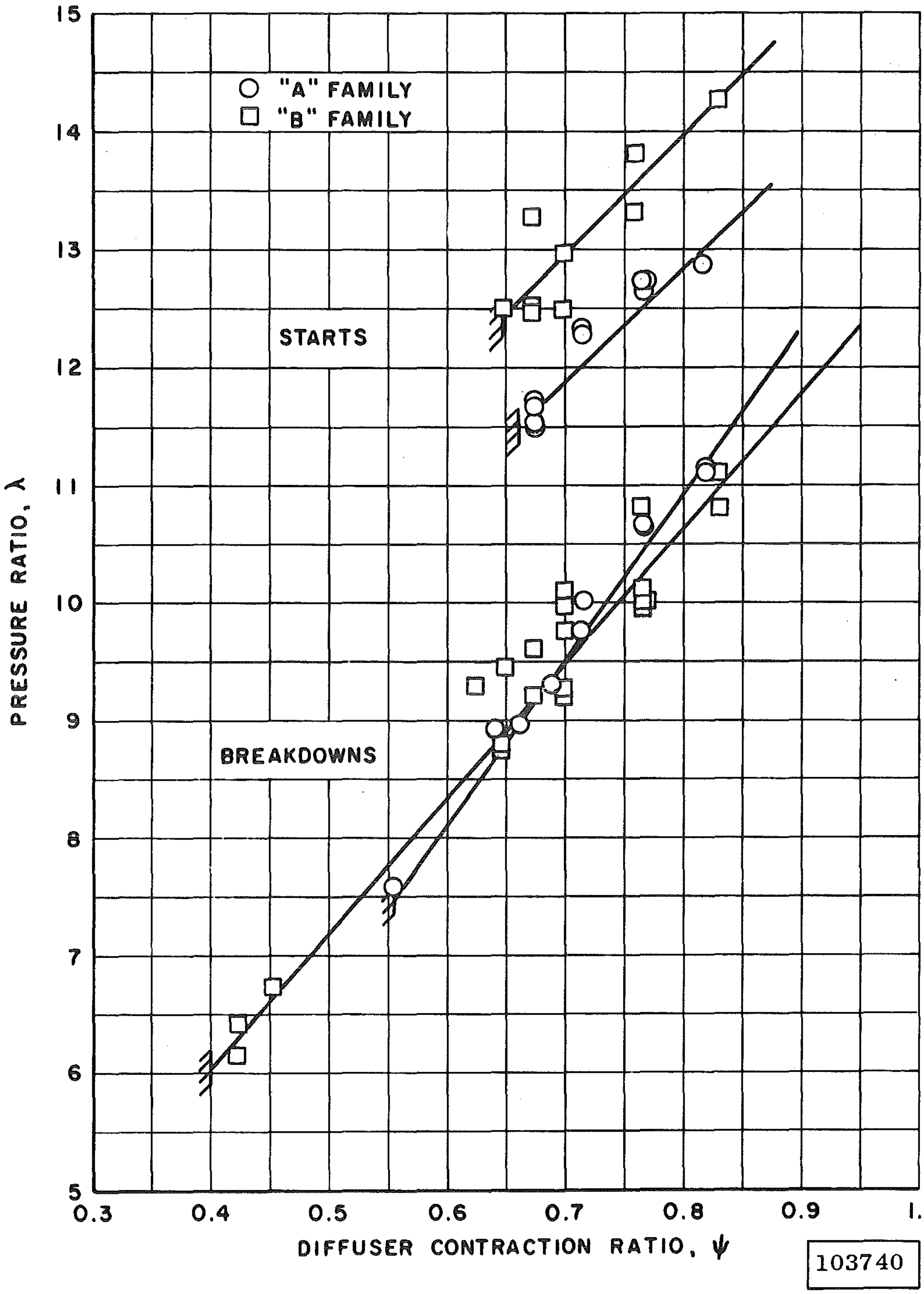
c. "B" Family Starts

Fig. 9 Continued



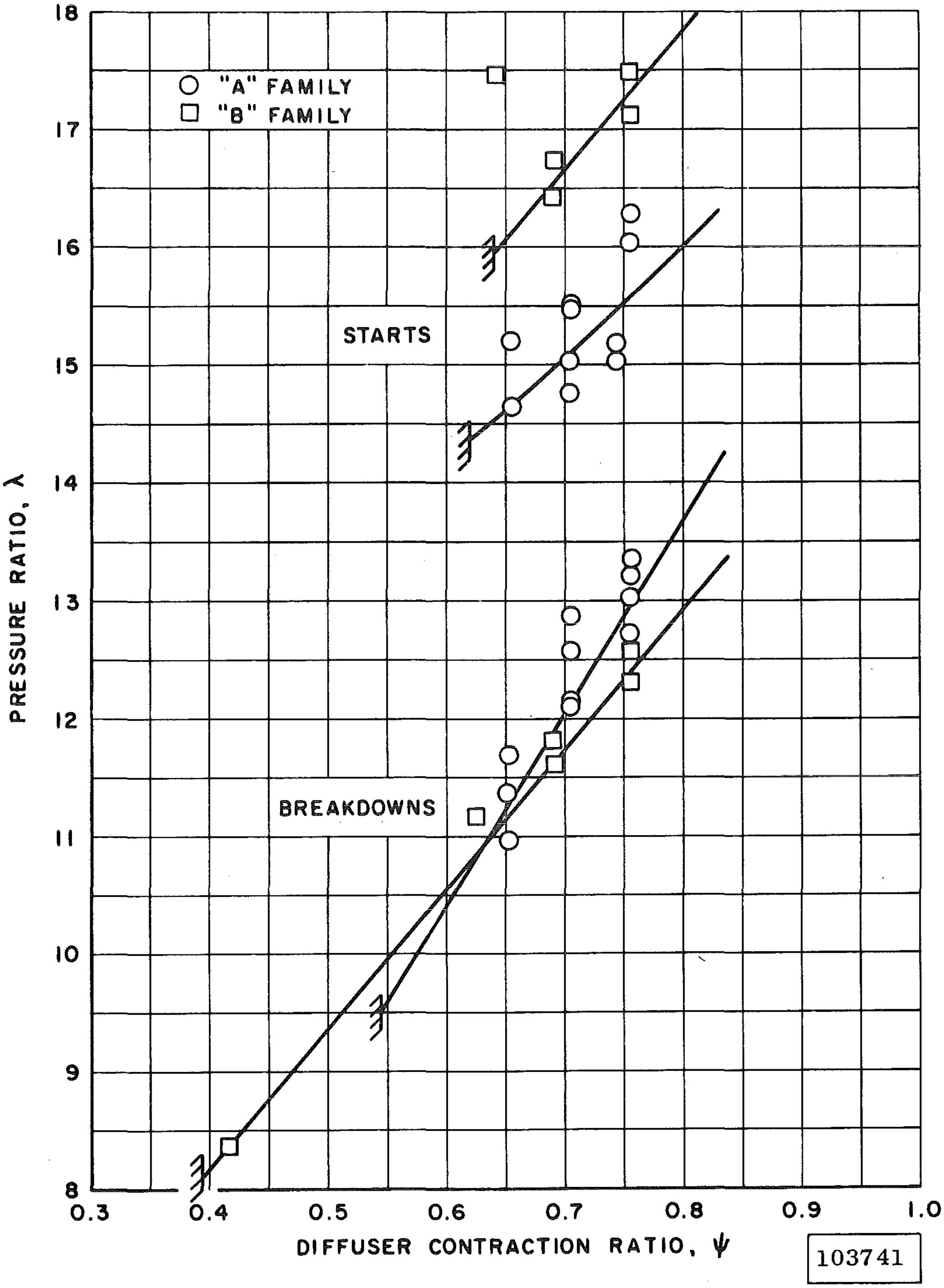
d. "B" Family Breakdowns

Fig. 9 Concluded



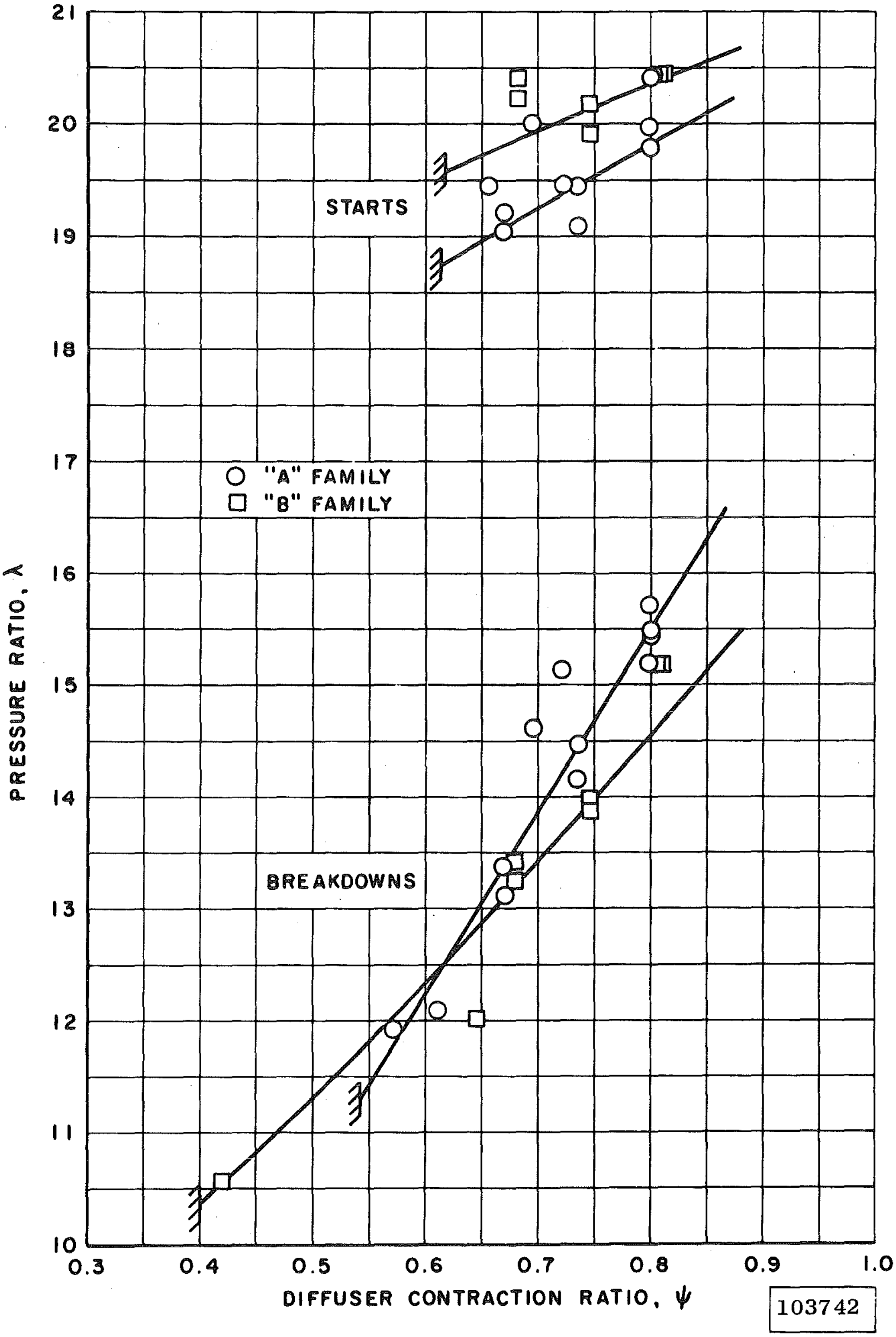
a. $M_\infty = 4.00$

Fig. 10 The "A" and "B" Families Starting and Running Performance at $M_\infty = 4.00, 4.25,$ and 4.50, θ_w Minimum, $\delta = 0$



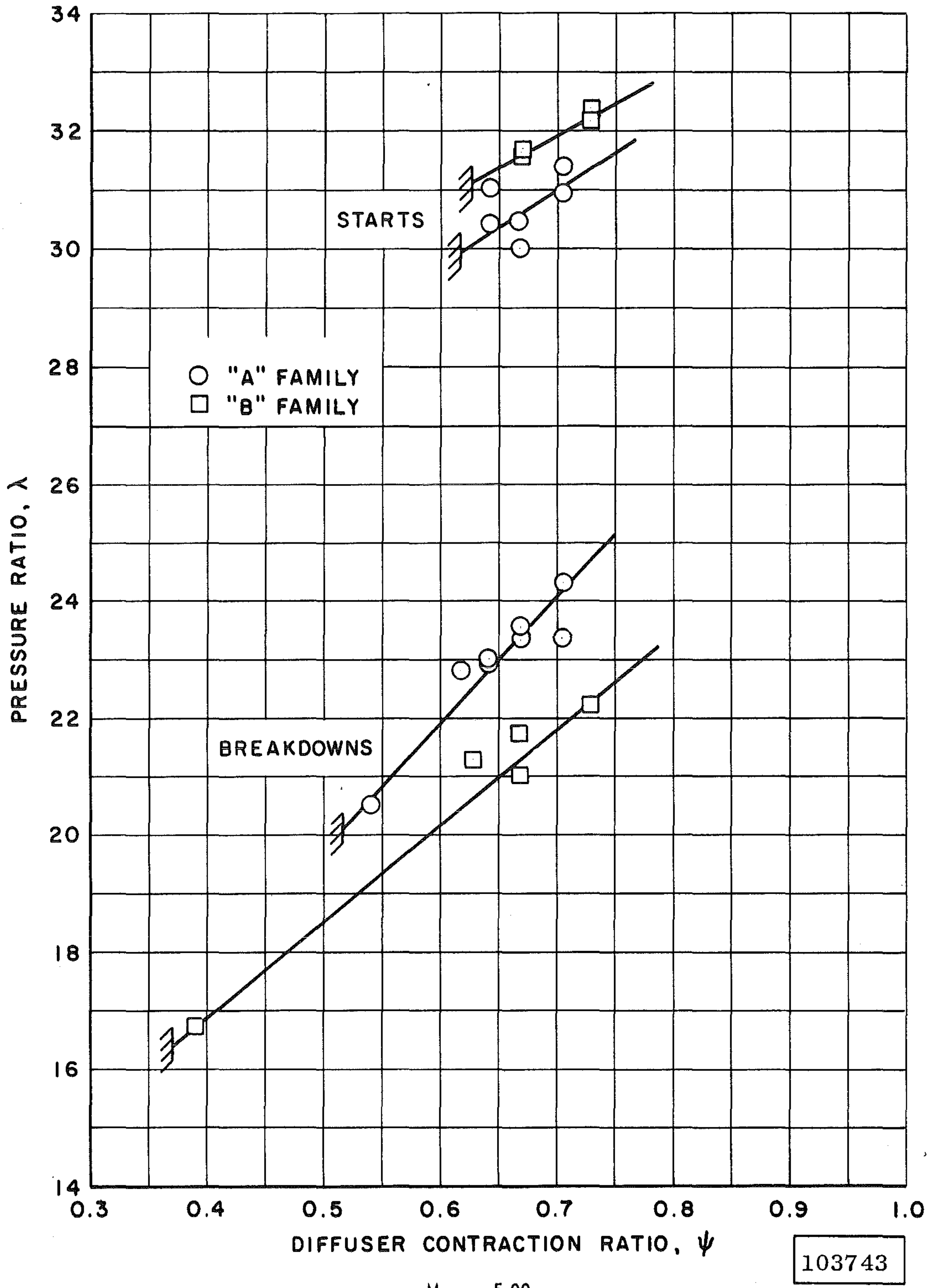
b. $M_\infty = 4.25$

Fig. 10 Continued



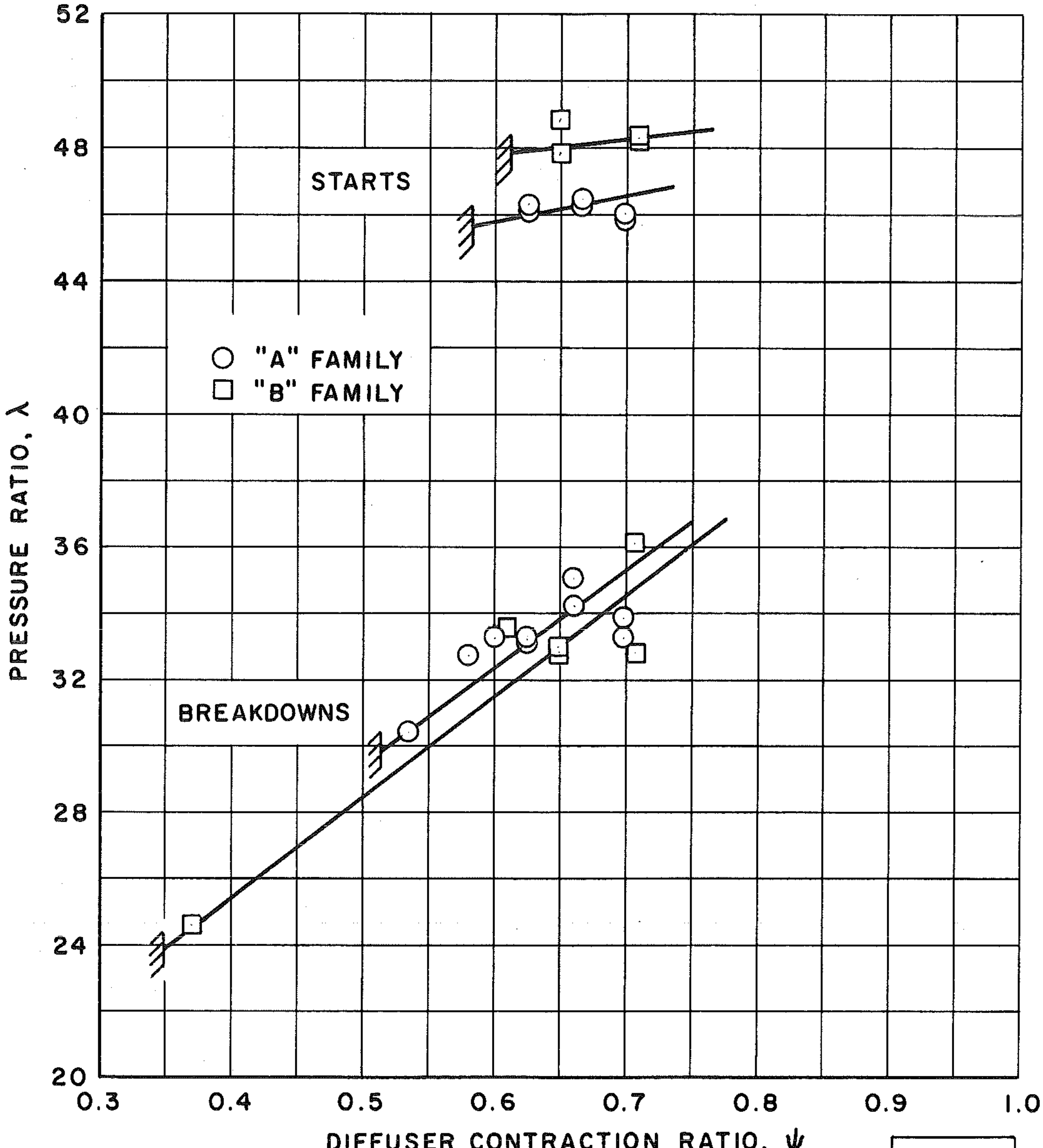
c. M_∞ = 4.50

Fig. 10 Concluded



a. M_∞ = 5.00

Fig. 11 The "A" and "B" Families Starting and Running Performance at M_∞ = 5.00, 5.50, and 5.85, θ_w Minimum, δ = 0



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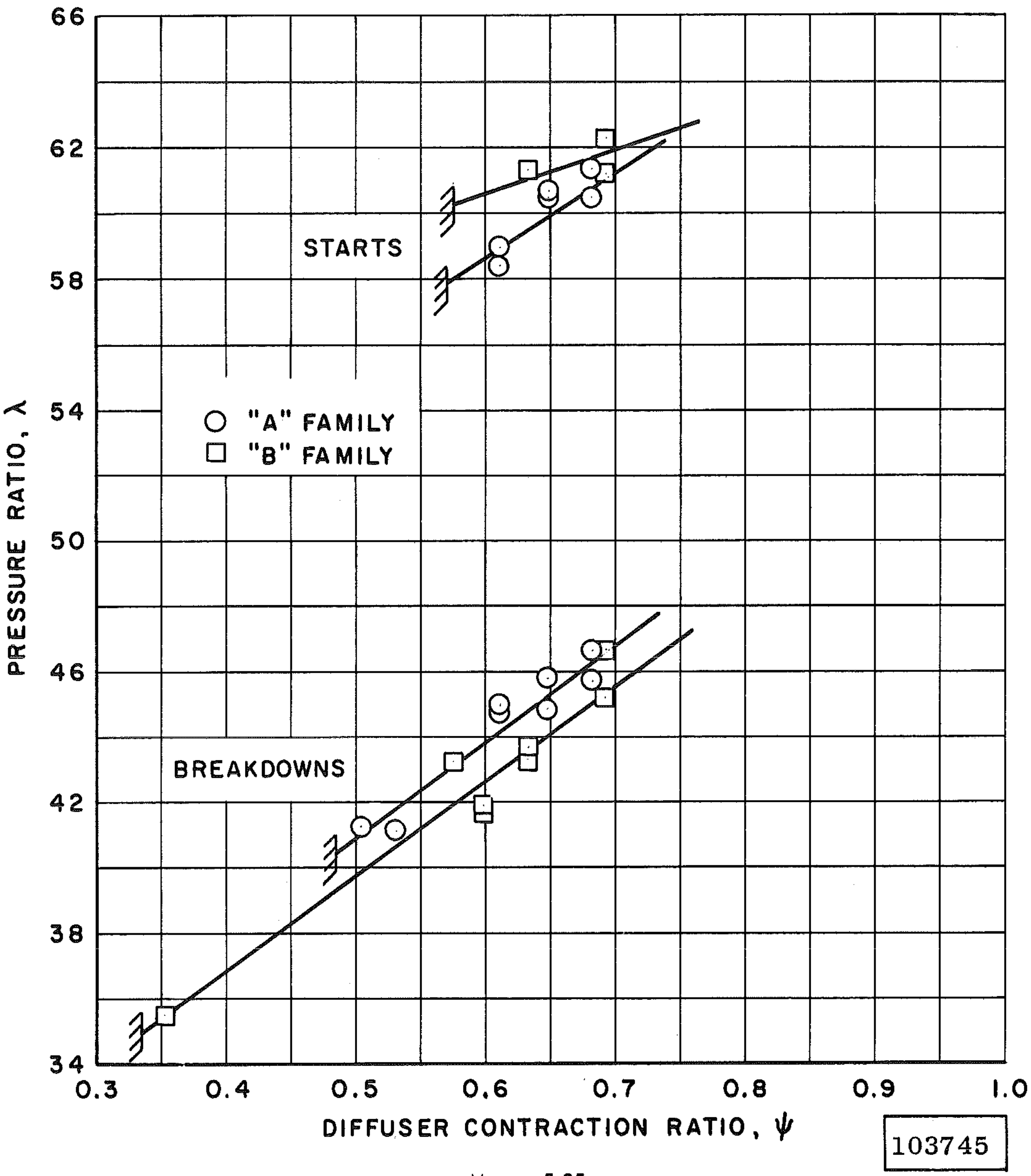
b. $M_\infty = 5.50$

Fig. 11 Continued



c. $M_\infty = 5.85$

Fig. 11 Concluded

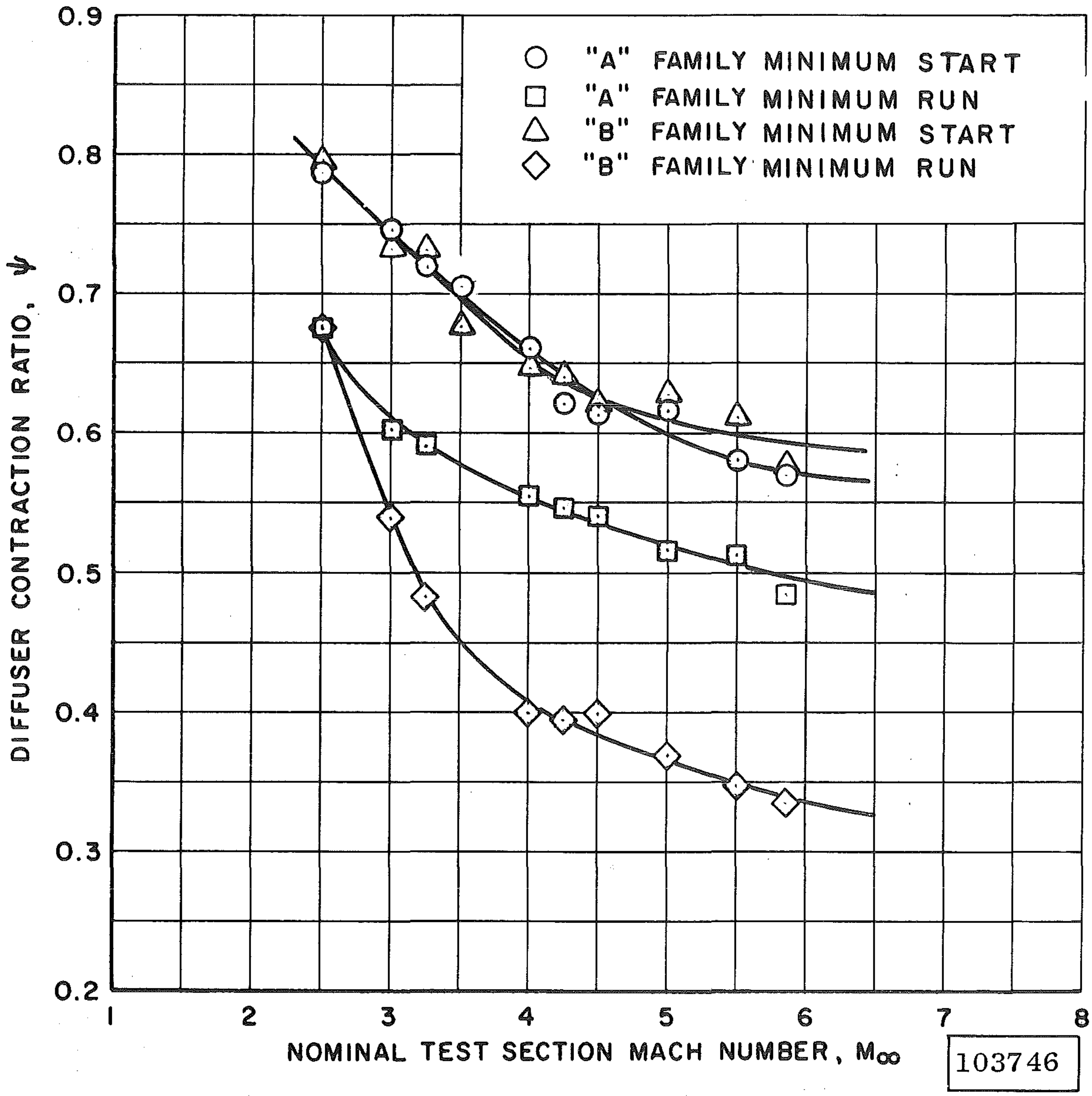
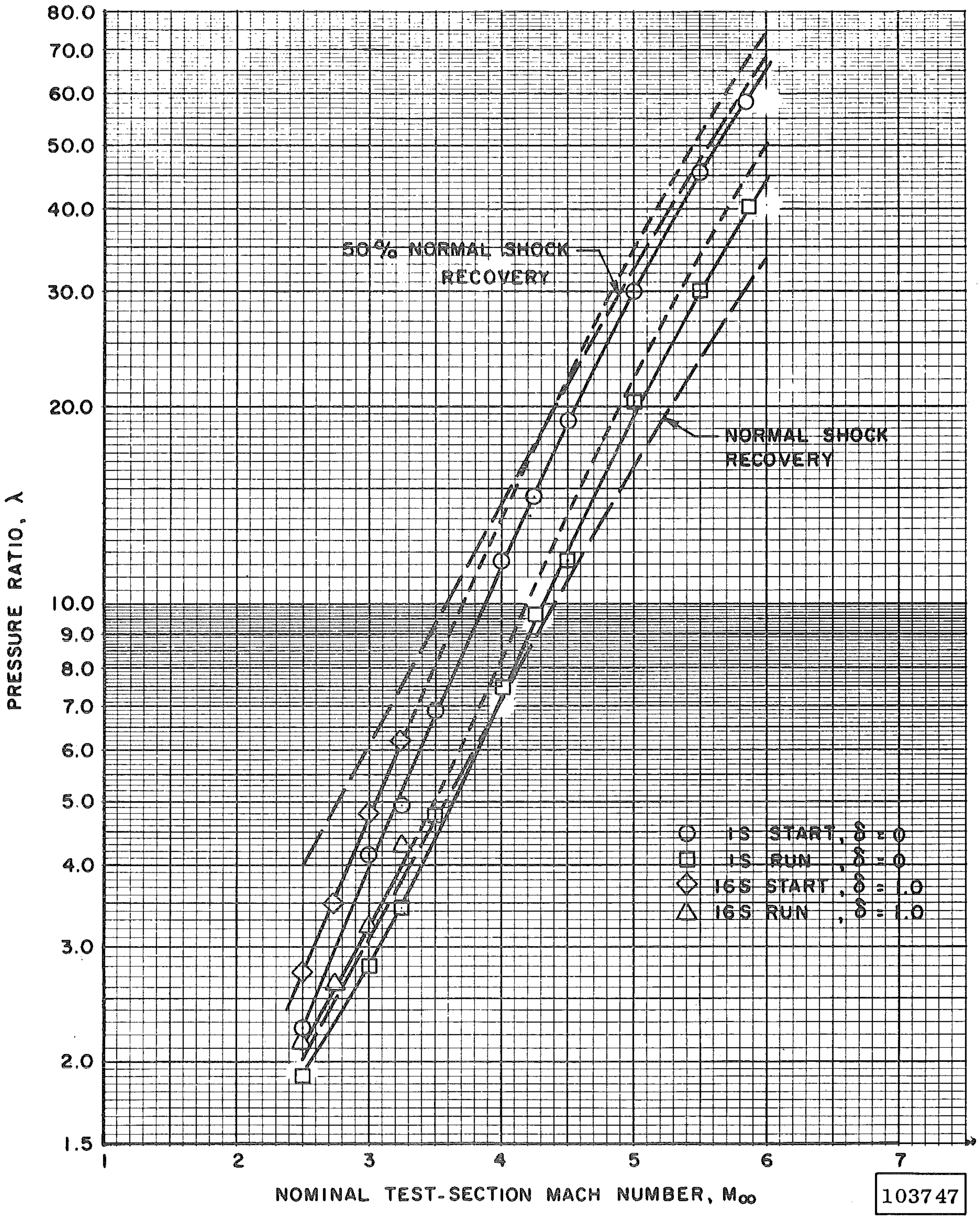
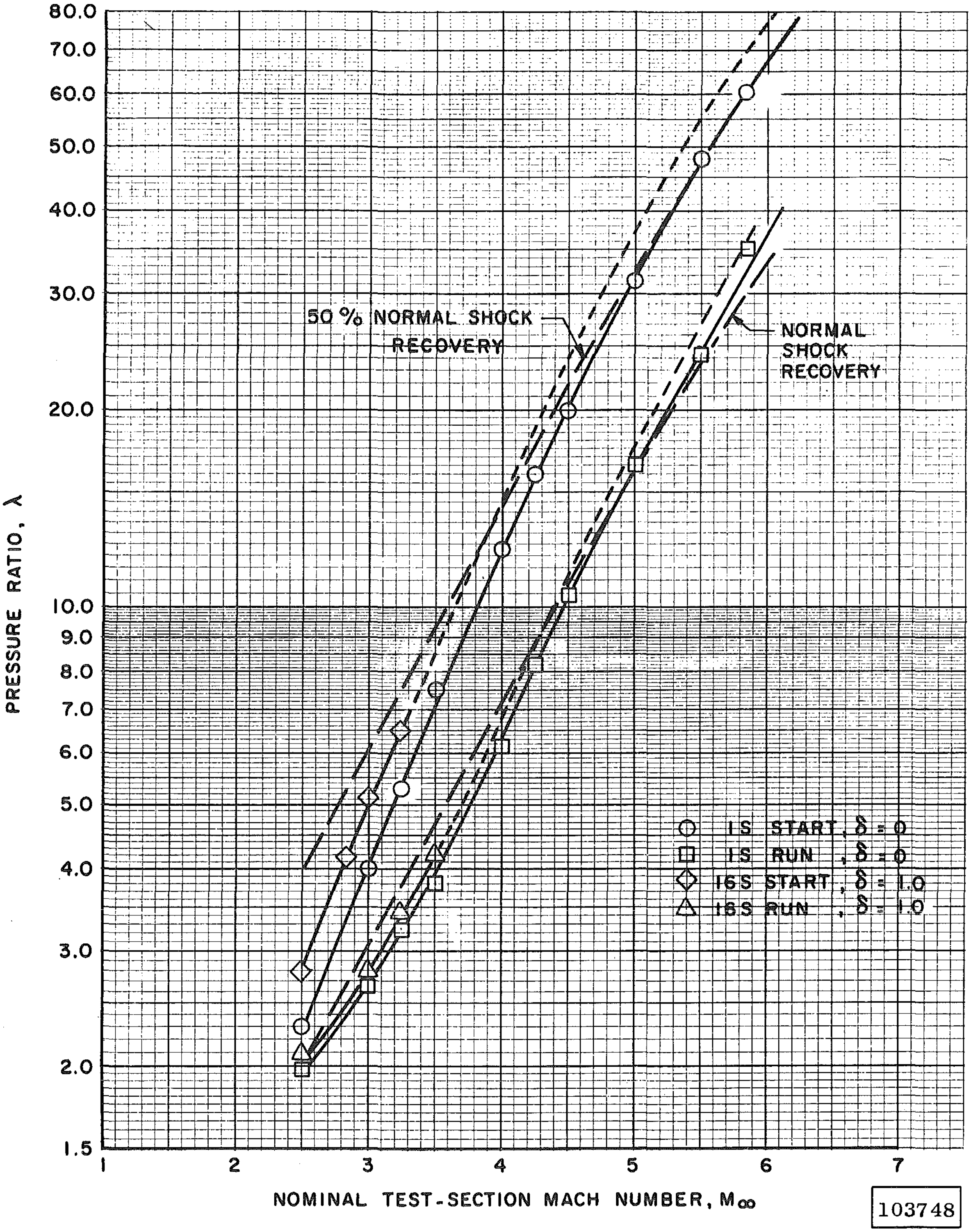


Fig. 12 Minimum Contraction Ratio for Starting and Running of the "A" and "B" Diffuser Families; θ_w Minimum, $\delta = 0$



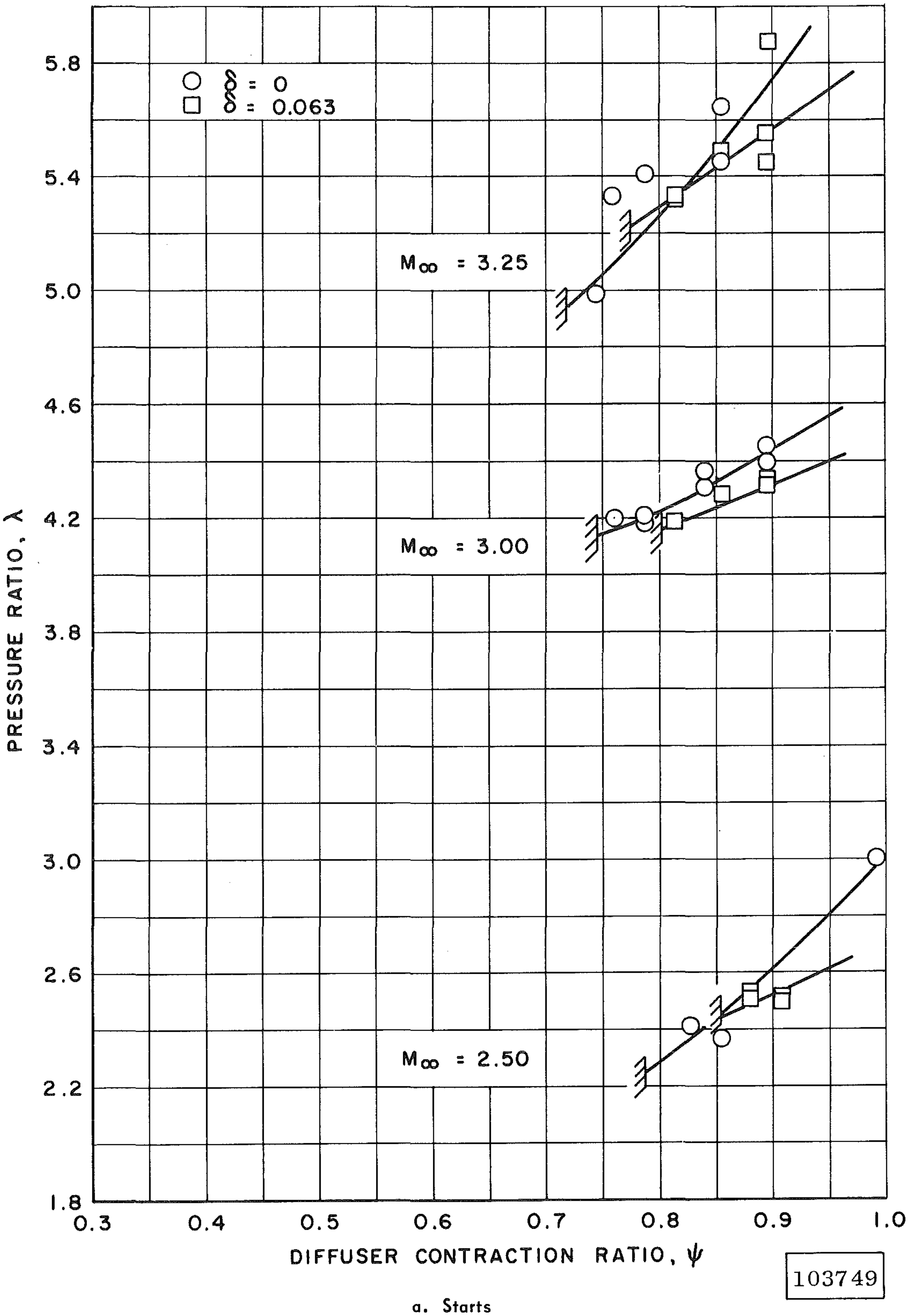
a. Diffuser Family "A"

Fig. 13 Minimum Starting and Running Pressure Ratio Requirements for Tunnel 1S with Some Correlation to Tunnel 16S



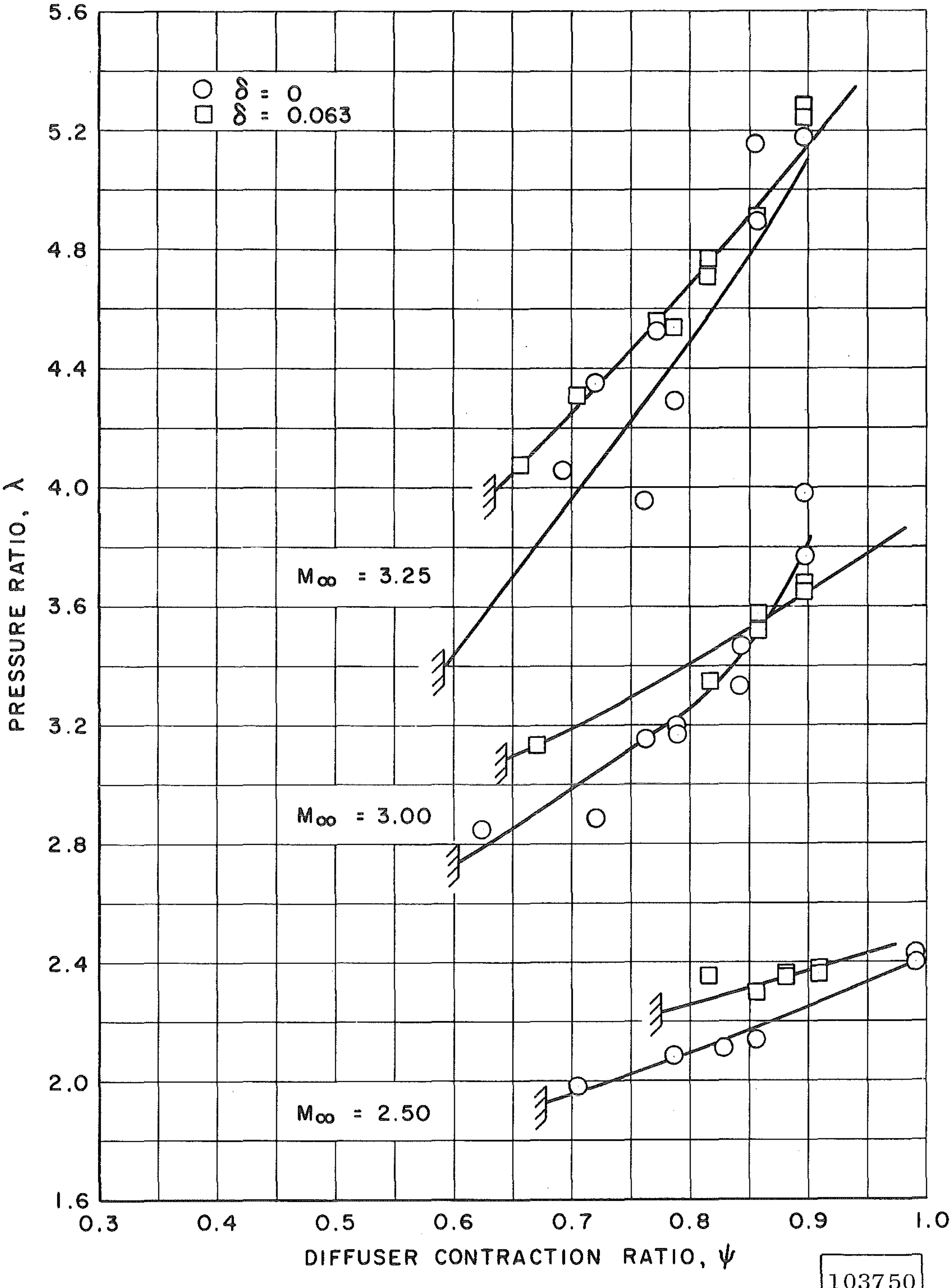
b. Diffuser Family "B"

Fig. 13 Concluded



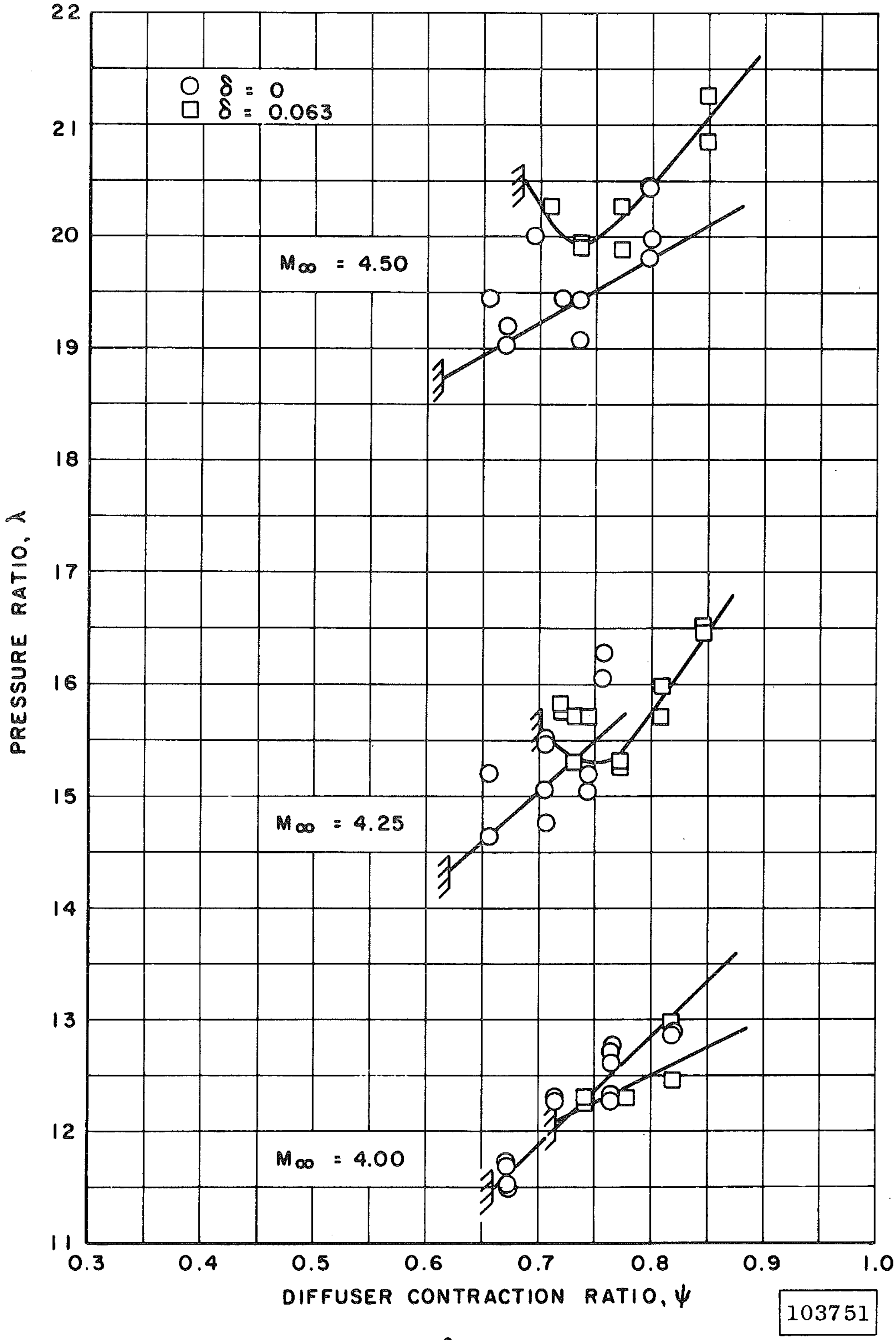
a. Starts

Fig. 14 Effect of Test Section-Diffuser Gap on the "A" Family Starting and Running Performance at M = 2.50, 3.00, and 3.25; θ_w = -30 min



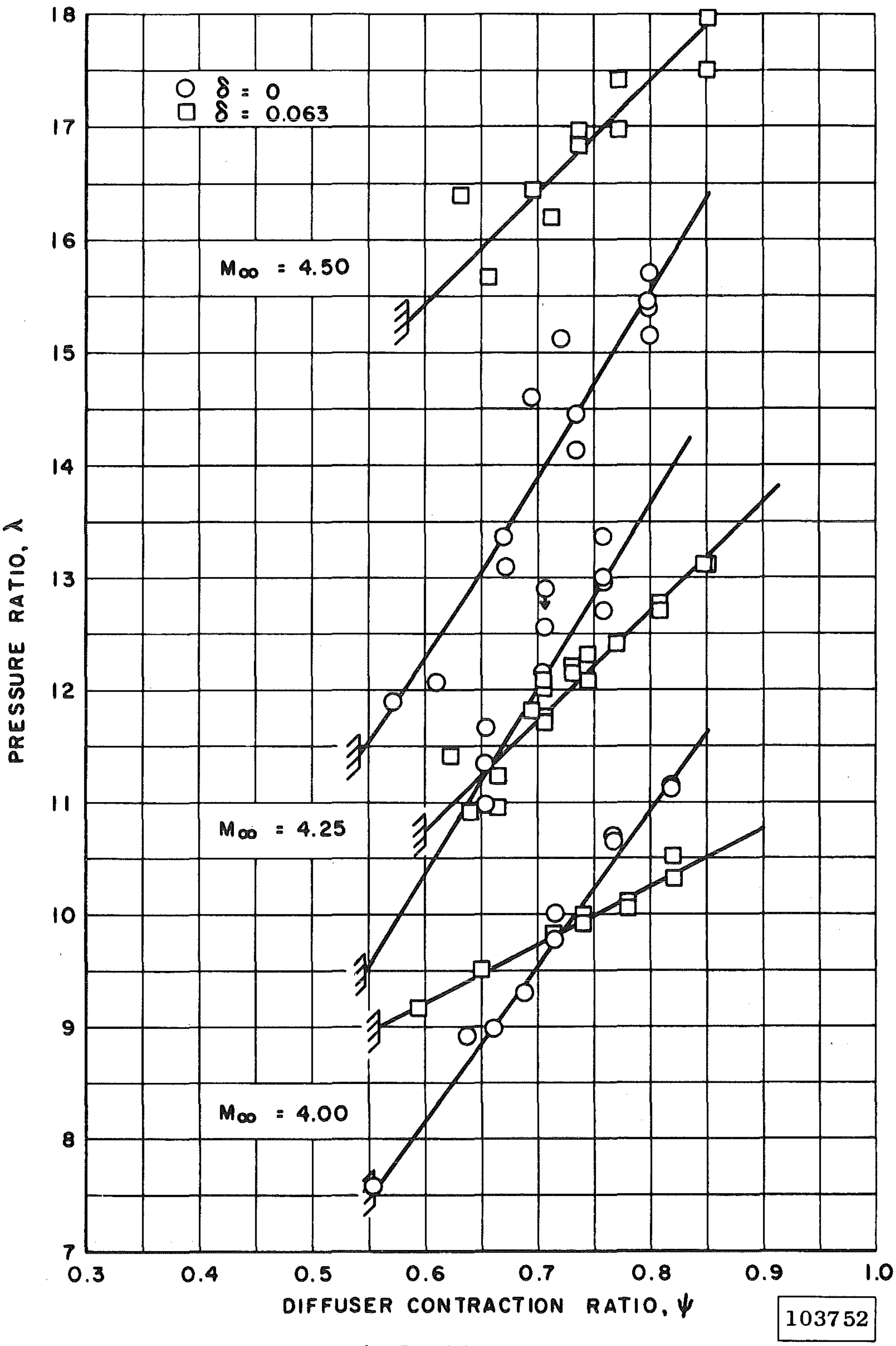
b. Breakdowns

Fig. 14 Concluded



a. Starts

Fig. 15 Effect of Test Section-Diffuser Gap on the "A" Family Starting and Running Performance at M_∞ = 4.00, 4.25, and 4.50; θ_w Minimum



b. Breakdowns

Fig. 15 Concluded

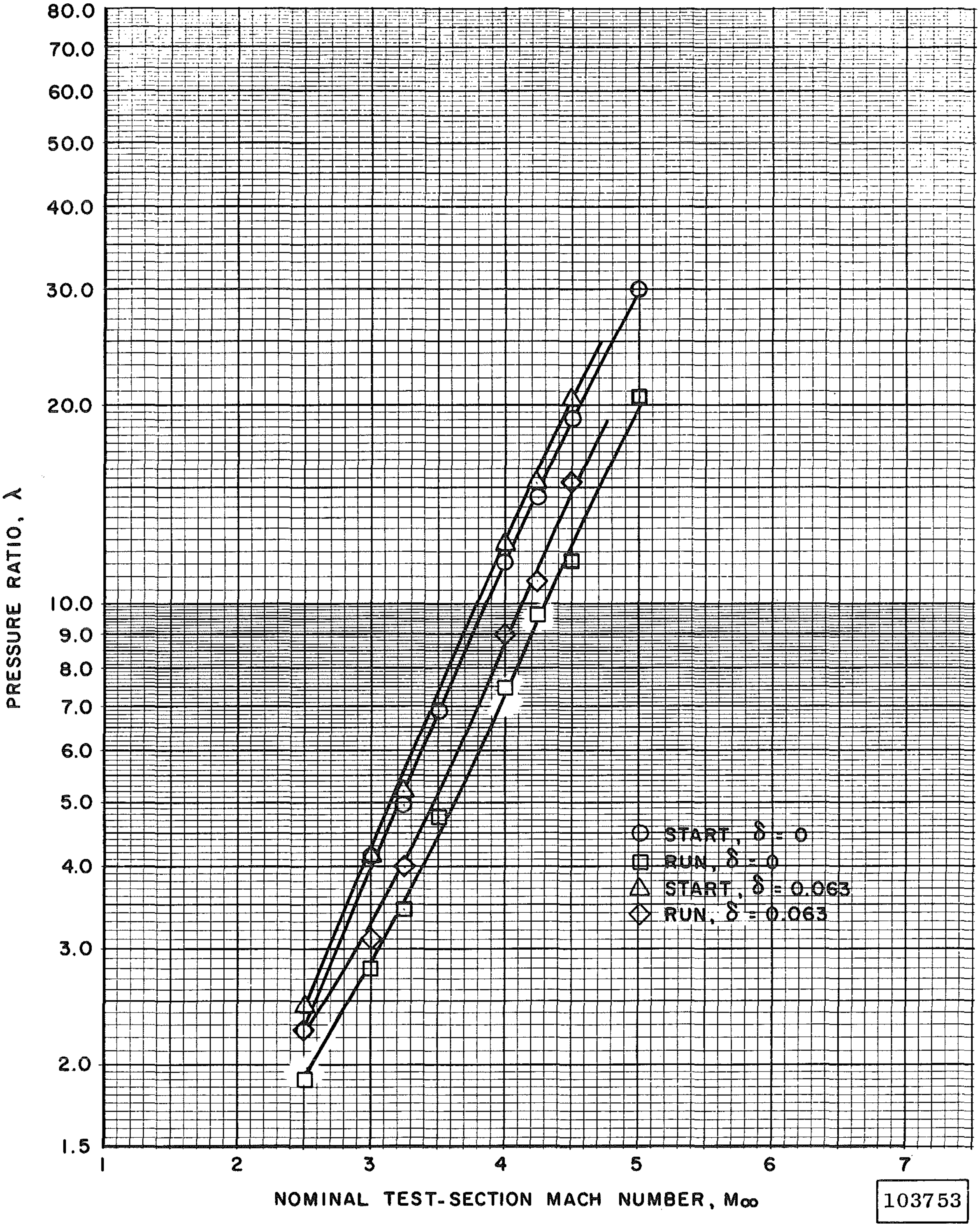


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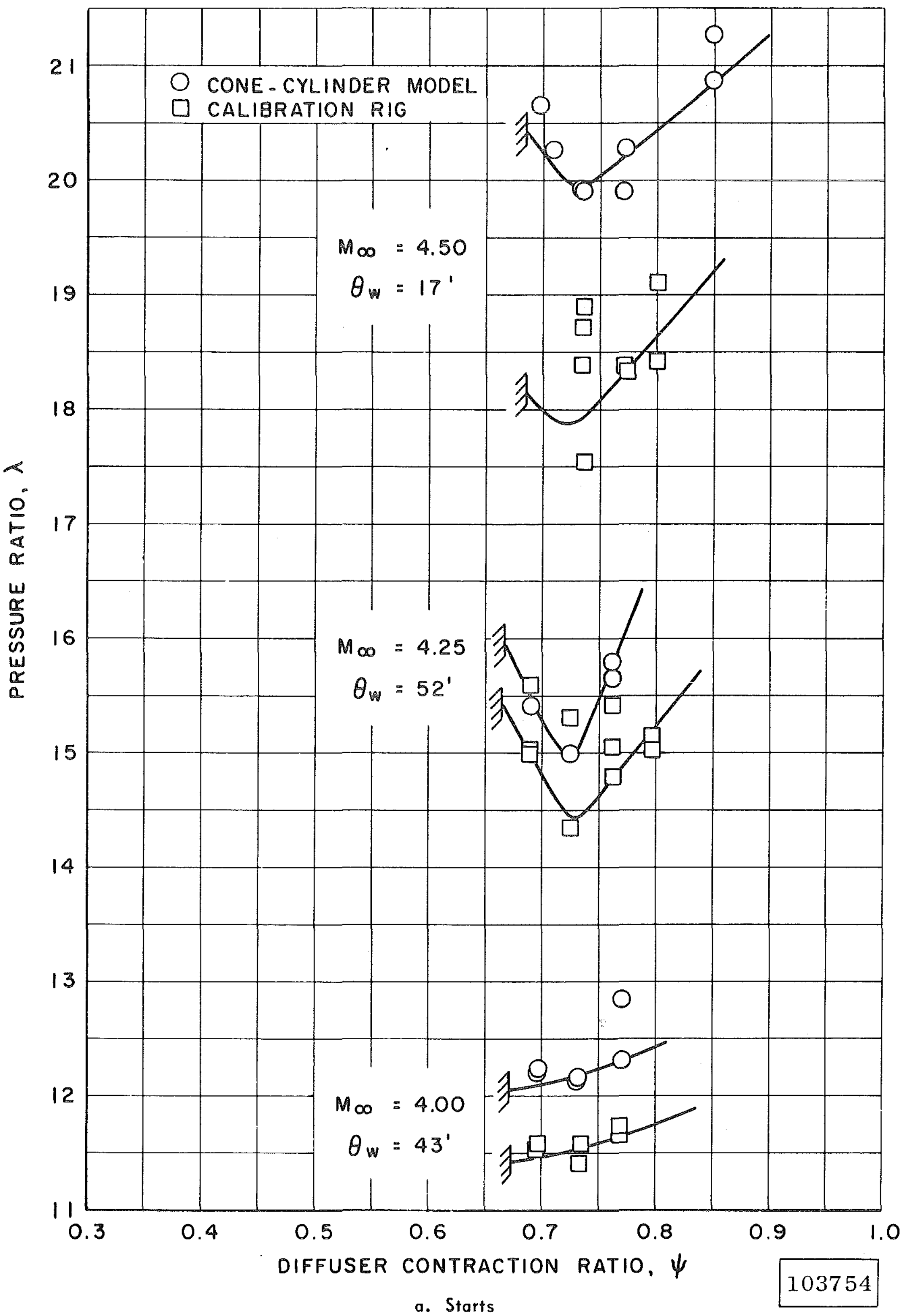
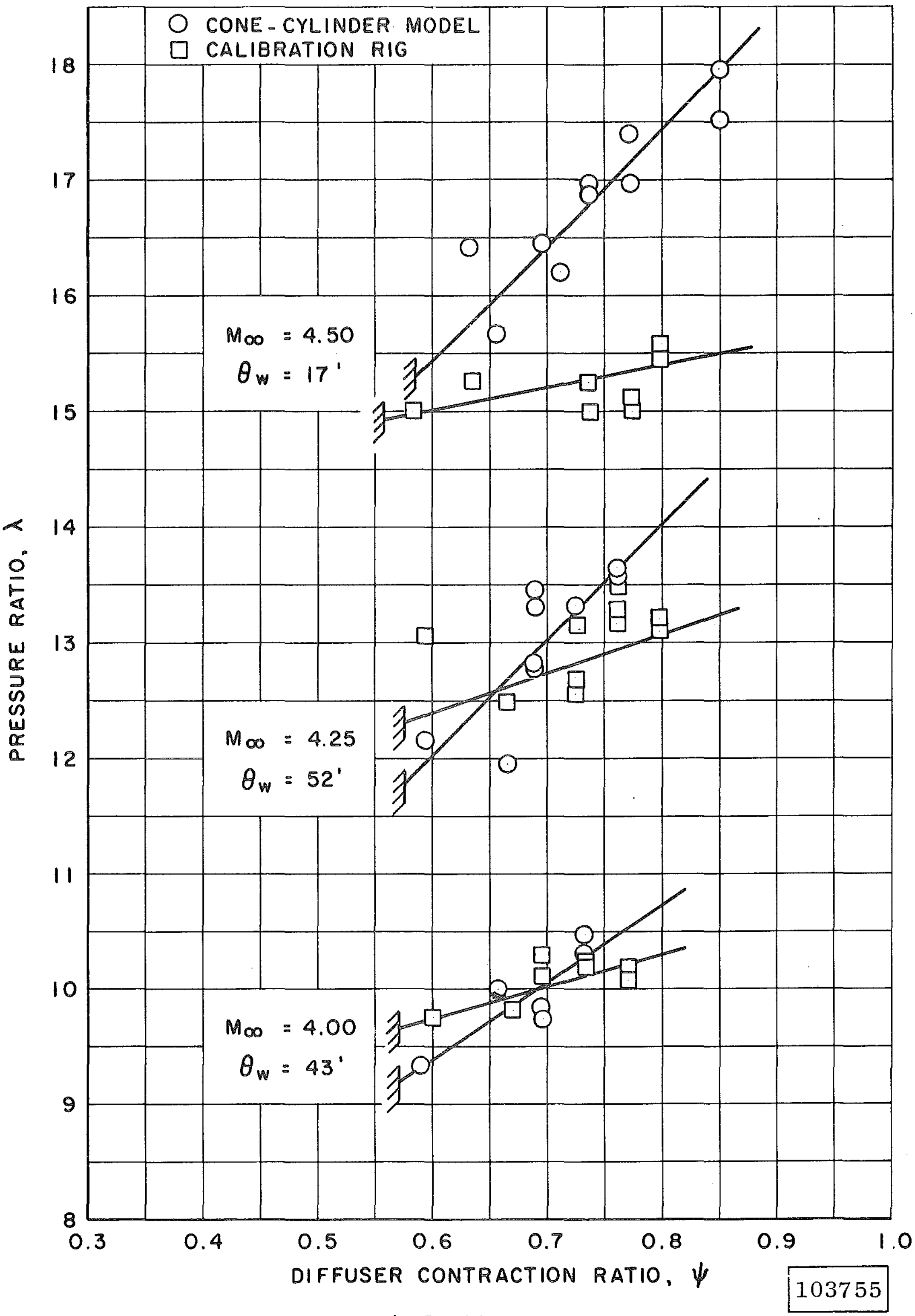
Fig. 16 Minimum "A" Family Starting and Running Pressure Ratio Requirements for Tunnel 1S with and without Test Section Diffuser Seals



a. Starts

Fig. 17 Effect of Test Section Installation on the "A" Family Starting and Running Performance at M_∞ = 4.00, 4.25, and 4.50, δ = 0.063



b. Breakdowns

Fig. 17 Concluded